PB80-212947

Field Tests of Industrial Stoker Coal-Fired Boilers for Emissions Control and Efficiency Improvement - Site H

KVB, Inc.
Minneapolis, MN

Prepared for

Industrial Environmental Research Lab.
Research Triangle Park, NC

May 80

U.S. Department of Commerce
National Technical Information Service
NTIS

PB80-212947

ABMA	American Boiler Manufacturers Association	1500 Wilson Boulevard Arlington VA 22209	
DoE	United States Department of Energy	Division of Power Systems Energy Technology Branch Washington DC 20545	
EPA	U.S. Environmental Protection Agency Office of Research and Development	Industrial Environmental Research Laboratory Research Triangle Park NC 27711	EPA-600/7-80-112a May 1980

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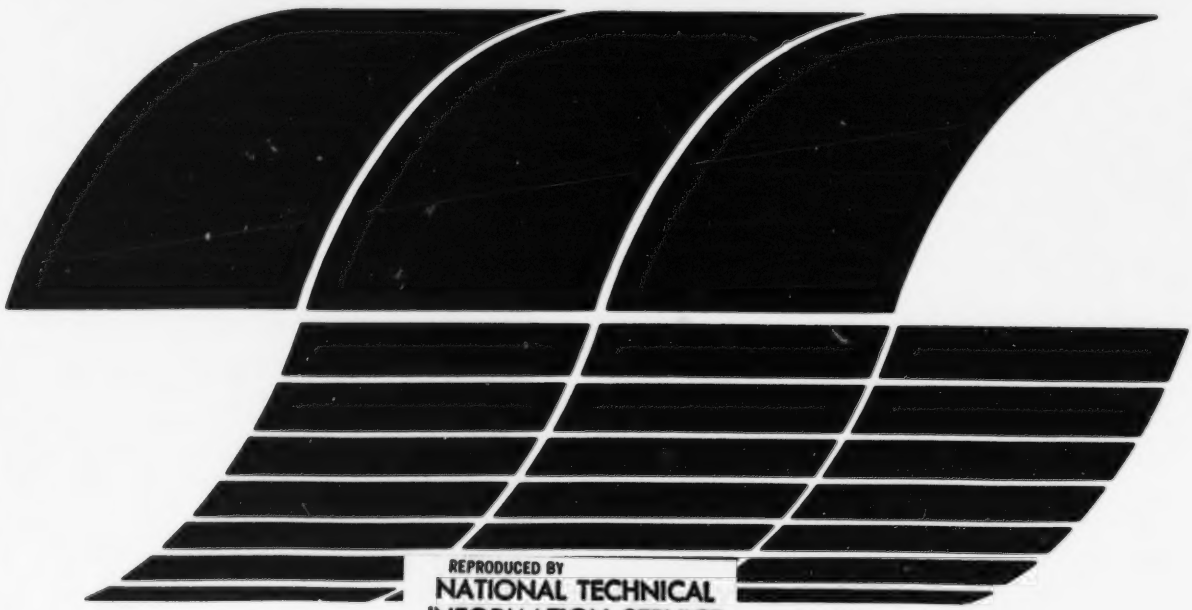
Interagency Energy/Environment R&D Program Report



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TECHNICAL REPORT DATA
(Please read Instructions on the reverse before completing)

1. REPORT NO. EPA-600/7-80-112a	2.
3. RECIPIENT'S ACCESSION NO. PB 80 212947	
4. TITLE AND SUBTITLE Field Tests of Industrial Stoker Coal-fired Boilers for Emissions Control and Efficiency Improvement--Site H	5. REPORT DATE May 1980
	6. PERFORMING ORGANIZATION CODE
7. AUTHOR(S) P. L. Langsjoen, R. J. Tidona, and J. E. Gabrielson	8. PERFORMING ORGANIZATION REPORT NO.
9. PERFORMING ORGANIZATION NAME AND ADDRESS KVB, Inc. 6176 Olson Memorial Highway Minneapolis, Minnesota 55422	10. PROGRAM ELEMENT NO. EHE624
	11. CONTRACT/GRANT NO. IAG-D7-E681 (EPA) and EF-77-C-01-2609 (DoE)
12. SPONSORING AGENCY NAME AND ADDRESS EPA, Office of Research and Development* Industrial Environmental Research Laboratory Research Triangle Park, NC 27711	13. TYPE OF REPORT AND PERIOD COVERED Final; 3/79-4/79
	14. SPONSORING AGENCY CODE EPA/600/13

15. SUPPLEMENTARY NOTES IERL-RTP project officer is R. E. Hall. (*) Cosponsors are DoE (W. T. Harvey Jr.) and the American Boiler Manufacturers Assoc. EPA-600/7-78-136a, -79-041a, -130a, -147a, -80-064a, -065a, and -082a are Site A-G reports.

16. ABSTRACT The report gives test results on a coal-fired, overfeed, traveling-grate stoker. The boiler tested is rated at 45,000 lb/hr saturated steam at 140 psig. Measurements include gaseous emissions (O_2, CO_2, CO, NO, NO_2, SO_3, and HC), uncontrolled particulate mass loading, particle size distribution of the flyash, combustible content of the bottom ash and flyash, and boiler efficiency. Measurements were made at loads representing 50, 75, and 100% of design capacity, several excess air levels, and both high- and low-overfire air pressure settings. Increased overfire air pressures decreased particulate loading, CO, and HC. Particulate loading was 1.0 lb/million Btu under full-load high-overfire-air conditions. NOx averaged 0.416 lb/million Btu (307 ppm) at full load.

17. KEY WORDS AND DOCUMENT ANALYSIS

a. DESCRIPTORS		b. IDENTIFIERS/OPEN ENDED TERMS	c. COSATI Field/Group	
Air Pollution	Improvement	Air Pollution Control	13B	14G
Boilers	Efficiency	Stationary Sources	13A	
Combustion	Flue Gases	Combustion Modification	21B	
Coal	Fly Ash	Spreader Stokers	21D	
Field Tests	Particle Size	Traveling Grate Stokers	14B	
Dust	Nitrogen Oxides	Particulate	11G	07B
Stokers	Sulfur Oxides	Overfire Air		

18. DISTRIBUTION STATEMENT Release to Public	19. SECURITY CLASS *(This Report)* Unclassified	21. NO. OF PAGES
	20. SECURITY CLASS *(This page)* Unclassified	22. PRICE

EPA Form 2220-1 (9-73)

EPA-600/7-80-112a

May 1980

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by

P.L. Langsjoen, R.J. Tidona,
and J.E. Gabrielson

KVB, Inc.
6176 Olson Memorial Highway
Minneapolis, Minnesota 55422

IAG/Contract Nos. IAG-D7-E681 (EPA), EF-77-C-01-2609 (DoE)
Program Element No. EHE624

EPA Project Officers: R.E. Hall (EPA) and W.T. Harvey, Jr. (DoE)

Industrial Environmental Research Laboratory
Office of Environmental Engineering and Technology
Research Triangle Park, NC 27711

Prepared for

U.S. ENVIRONMENTAL PROTECTION AGENCY
Office of Research and Development
Washington, DC 20460

U.S. DEPARTMENT OF ENERGY
Division of Power Systems/Energy Technology Branch
Washington, DC 20545

and

AMERICAN BOILER MANUFACTURERS ASSOCIATION
1500 Wilson Boulevard
Arlington, VA 22209

ACKNOWLEDGEMENTS

The authors wish to express their appreciation for the assistance and direction given the program by project monitors W. T. (Bill) Harvey of the United States Department of Energy (DOE) and R. E. (Bob) Hall of the United States Environmental Protection Agency (EPA). Thanks are due to their agencies, DOE and EPA, for co-funding the program.

We would also like to thank the American Boiler Manufacturers Association, ABMA Executive Director, W. H. (Bill) Axtman, ABMA Assistant Executive Director, R. N. (Russ) Mosher, ABMA's Project Manager, B. C. (Ben) Severs, and the members of the ABMA Stoker Technical Committee chaired by W. B. (Willard) McBurney of the McBurney Corporation for providing support through their time and travel to manage and review the program. The participating committee members listed alphabetically are as follows:

R. D. Bessette	Island Creek Coal Company
T. Davis	Combustion Engineering
N. H. Johnson	Detroit Stoker
K. Luuri	Riley Stoker
D. McCoy	E. Keeler Company
J. Mullan	National Coal Association
E. A. Nelson	Zurn Industries
E. Poitras	The McBurney Corporation
P. E. Ralston	Babcock and Wilcox
D. C. Reschley	Detroit Stoker
R. A. Santos	Zurn Industries

We would also like to recognize the KVB engineers and technicians who spent much time in the field, often under adverse conditions, testing the boilers and gathering data for this program. Those involved at Site H were Mike Gabriel, Jon Cook, Mike Jackson, Mike Bakalor and Mark Shumaker.

Finally, our gratitude goes to the host boiler facilities which invited us to test their boilers. At their request, the facilities will remain anonymous to protect their own interests. Without their cooperation and assistance this program would not have been possible.

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1.0 INTRODUCTION

The principal objective of the test program described in this report, one of several reports in a series, is to produce information which will increase the ability of boiler manufacturers to design and fabricate stoker boilers that are an economical and environmentally satisfactory alternative to oil-fired units. Further objectives of the program are to: provide information to stoker boiler operators concerning the efficient operation of their boilers; provide assistance to stoker boiler operators in planning their coal supply contracts; refine application of existing pollution control equipment with special emphasis on performance; and contribute to the design of new pollution control equipment.

In order to meet these objectives, it is necessary to define stoker boiler designs which will provide efficient operation and minimum gaseous and particulate emissions, and define what those emissions are in order to facilitate preparation of attainable national emission standards for industrial size, coal-fired boilers. To do this, boiler emissions and efficiency must be measured as a function of coal analysis and sizing, rate of flyash reinjection, overfire air admission, ash handling, grate size, and other variables for different boiler, furnace, and stoker designs.

A field test program designed to address the objectives outlined above was awarded to the American Boiler Manufacturers Association (ABMA), sponsored by the United States Department of Energy (DOE) under contract number EF-77-C-01-2609, and co-sponsored by the United States Environmental Protection Agency (EPA) under inter-agency agreement number IAG-D7-E681. The program is directed by an ABMA Stoker Technical Committee which, in turn, has subcontracted the field test portion to KVB, Inc., of Minneapolis, Minnesota.

This report is the Final Technical Report for the eighth of eleven boilers to be tested under the ABMA program. It contains a description of the facility tested, the coals fired, the test equipment and procedures, and the results and observations of testing. There is also a data supplement to this report containing the "raw" data sheets from the tests conducted. The

data supplement has the same EPA report number as this report except that it is followed by "b" rather than "a". As a compilation of all data obtained at this test site, the supplement acts as a research tool for further data reduction and analysis as new areas of interest are uncovered in subsequent testing.

At the completion of this program, a Final Technical Report will combine and correlate the test results from all sites tested. A report containing operating guidelines for boiler operators will also be written, along with a separate report covering trace species data. These reports will be available to interested parties through the NTIS or through the EPA's Technical Library.

Although it is EPA policy to use S.I. units in all EPA sponsored reports, an exception has been made herein because English units have been conventionally used to describe boiler design and operation. Conversion tables are provided in the Appendix for those who prefer S.I. units.

To protect the interests of the host boiler facilities, each test site in this program has been given a letter designation. As the eighth site tested, this is the Final Technical Report for Test Site H under the program entitled, "A Testing Program to Update Equipment Specifications and Design Criteria for Stoker Fired Boilers."

2.0 EXECUTIVE SUMMARY

A coal fired overfeed stoker rated at 45,000 lbs steam/hr was tested for emissions and efficiency at three loads and under various conditions of excess air and overfire air. Testing was conducted between March 19, 1979, and April 4, 1979. This section summarizes the results of these tests and provides references to supporting figures, tables and commentary found in the main text of the report.

UNIT TESTED: Described in Section 3.0 pages 9-14.

- Bros Boiler

  Built 1959
  45,000 lb/hr rated capacity
  140 psig operating steam pressure
  Saturated steam
  No economizer or air heater
  No dust collector

- Riley Traveling Grate Stoker

  Mass Fired
  Harrington Traveling Grate
  No flyash reinjection
  One row OFA jets on front water wall

COAL TESTED: Coal from one mine was tested. Individual coal analysis are given in Tables 5-12 and 5-13, pages 63 and 64. Commentary in Section 3.4, page 13, and Section 5.3, page 62.

- Sands Hill Coal

  11,417 Btu/lb
  8.62% Ash
  1.88% Sulfur
  11.56% Moisture
  2205°F Initial ash deformation temperature
  25.9% Fines

OVERFIRE AIR TEST RESULTS: This unit was normally operated with a low overfire air setting of about 3" H_2O pressure at all loads. During two tests the overfire air pressure was increased to about 11.5" H_2O. In addition, overfire air flow rate was determined at two pressure settings (Section 5.1, page 33, Table 5-1, page 34).

- Particulate Loading

  Increasing overfire air pressure from 2.7 to 11.7" H_2O while maintaining undergrate air flow constant resulted in a 50% reduction in uncontrolled particulate loading (Section 5.1.1, page 33).

- Nitric Oxide

  Nitric oxide concentrations were unaffected by changes in overfire air pressure (Section 5.1.2, page 35).

- Carbon Monoxide and Unburned Hydrocarbons

  Both carbon monoxide and unburned hydrocarbon concentrations were reduced significantly when overfire air pressure was increased at high loads (Section 5.1.3, page 36).

- Boiler Efficiency

  Data is inconclusive (Section 5.1.4, page 37).

- Overfire Air Flow Rate

  Overfire air was found to supply 12% of the combustion air at 100% capacity, 11.5" H_2O pressure in the overfire air duct, and 8% O_2. Data is supplied for determining overfire air flow rate as a function of pressure (Section 5.1.5, page 37).

BOILER EMISSION PROFILES: Boiler emissions and efficiency were measured over the load range 50-102% of design capacity, which corresponds to a grate heat release range of 212,000 to 432,000 Btu/hr-ft^2. Measured oxygen levels ranged from 5.3 to 13.7% (Section 5.2, page 38).

- Excess Oxygen Operating Levels

  The optimum oxygen operating level was determined to be 8.0% at medium and high loads. Below 8% O_2, clinker formation was excessive (Section 5.2.1, page 40).

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- Particulate Loading

  Particulate loading at full load was 0.90 and 1.13 lb/10^6 Btu under high overfire air conditions, and 2.20 lb/10^6 Btu under low overfire air conditions. Particulate loading dropped to 0.55 and 0.68 lb/10^6 Btu at 75% and 50% boiler capacity, respectively. Ash carryover averaged 7% of the ash in the fuel (Section 5.2.2, page 40).

- Nitrogen Oxides

  Nitric oxide was more sensitive to oxygen at high loads than at lower loads. At full load, nitric oxide increased by 0.055 lb/10^6 Btu for each one percent increase in oxygen. At 75% capacity the slope was 0.040 and at 50% capacity it was 0.019 lb NO/10^6 Btu for each one percent O_2 increase. Nitric oxide (NO) averaged 0.416 lb/10^6 Btu (307 ppm) at full loads and less at lower loads. Nitrogen dioxide (NO_2) averaged 0.004 lb/10^6 Btu (3 ppm) at all loads (Section 5.2.3, page 43).

- Sulfur Oxides

  Sulfur retention in the ash averaged 3.3%. The remaining 96.7% of the fuel sulfur was converted to SO_2 and SO_3; with SO_3 accounting for less than 2% of the total (Section 5.2.4, page 45).

- Hydrocarbons

  Unburned hydrocarbons averaged 51 ppm at full load, 78 ppm at 75% capacity and 104 ppm at 50% capacity. They were found to be dependent on oxygen, increasing as oxygen increased at constant load (Section 5.2.5, page 53).

- Carbon Monoxide

  Carbon monoxide remained below 400 ppm except at high loads below 6% O_2 and low loads above 13% O_2 (Section 5.2.6, page 53).

- Combustibles in the Ash

  Combustibles in the flyash ranged from 23 to 33% by weight. Combustibles in the bottom ash ranged from 7 to 21% by weight. Both decreased slightly at full load and showed no correlation with oxygen (Section 5.2.7, page 58).

BOILER EFFICIENCY: Boiler efficiency averaged 75.4% at full load, and was 79.2% at 75% of capacity and 77.5% at 50% of capacity. The drop in efficiency at full load was due to an increase in stack temperature (Section 5.2.8, page 58).

PARTICLE SIZE DISTRIBUTION OF FLYASH: Three particle size distribution measurements were made of the flyash using three different techniques. Results vary with measurement technique (Section 5.4, page 67).

SOURCE ASSESSMENT SAMPLING SYSTEM: During one test flue gas was sampled for polynuclear aromatic hydrocarbons and trace elements. Test results will be presented in a separate report at completion of test program (Section 5.5, page 71).

The test plan and the emissions data are summarized in Tables 2-1 and 2-2 on the following pages. Other data tables are included at the end of Section 5.0, Test Results and Observations. For reference, a Data Supplement containing all the unreduced data obtained at Site H is available under separate cover but with the same title followed by the words "Data Supplement," and having the same EPA document number followed by the letter "b" rather than "a". Copies of this report and the Data Supplement are available through EPA and NTIS.

TABLE 2-1

TEST PLAN FOR TEST SITE H

FIRING CONDITIONS			TEST MEASUREMENTS						
% Boiler Capacity	Excess Air	Overfire Air	Flue Gas Composition	Particulate Loading	Particle Size Distribution	SASS	SO_3	Overfire Air Flow Rate	Test No.
100	Vary	Low	X						1, 2
100	Low	Low	X	X	X				3
100	Low	High	X	X	X				5
100	High	High	X	X					6
100	Low	Low	X		X	X	X		11
75	Vary	Low	X						7
75	Norm	Low	X	X					8
50	Vary	Low	X						10
50	Norm	Low	X	X					9
50	Norm	Vary	X					X	4

TABLE 2-2

EMISSION DATA SUMMARY
TEST SITE H

Test No.	Date	% Design Capacity	Coal	Excess Air	O_2 % dry	CO_2 % dry	CO* ppm dry	NO* ppm dry	NO $lb/10^6Btu$	NO_2 $lb/10^6Btu$	SO_2 $lb/10^6Btu$	HC* ppm wet	Uncontrolled Particulate $10/10^6Btu$	Special Tests or Conditions
1A	3/19/79	88	S	72	9.2	9.2	153	305	0.413	--	--	--	--	
1B	3/19/79	88	S	91	10.5	7.6	239	360	0.488	--	--	--	--	
2A	3/20/79	96	S	49	7.2	11.0	163	270	0.366	0.000	3.014	OOS	--	
2B	3/21/79	96	S	62	8.4	9.6	96	275	0.373	0.000	2.415	OOS	--	
2C	3/21/79	96	S	88	10.3	7.9	274	367	0.497	0.000	2.836	OOS	--	
2D	3/21/79	96	S	73	9.3	8.9	196	276	0.374	0.005	3.258	OOS	--	
2E	3/21/79	96	S	66	8.8	8.8	162	312	0.423	0.000	3.693	OOS	--	
2F	3/21/79	96	S	53	7.7	9.7	712	226	0.306	0.000	3.116	OOS	--	
3	3/22/79	102	S	58	8.0	10.8	513	274	0.371	0.018	2.617	OOS	2.195	Bahco
4	3/23/79	50	S	81	9.8	8.4	41	279	0.378	--	--	--	--	
5	3/26/79	99	S	76	9.4	9.2	41	339	0.459	0.001	3.524	5	1.130	Brink, High OFA
6	3/27/79	97	S	97	10.6	9.1	69	331	0.448	0.012	3.378	35	0.897	High OFA
7A	3/28/79	76	S	60	8.2	10.3	56	207	0.280	0.001	5.066	29	--	
7B	3/28/79	76	S	141	12.8	5.7	340	344	0.466	0.014	7.358	132	--	
7C	3/28/79	76	S	88	10.1	9.4	99	314	0.425	0.003	6.383	99	--	
7D	3/28/79	76	S	32	5.3	13.2	665	161	0.218	0.000	4.429	64	--	
8	3/29/79	75	S	60	8.2	10.3	76	196	0.266	0.000	4.539	68	0.545	
9	3/30/79	52	S	114	11.6	7.3	148	244	0.331	0.001	3.770	94	0.681	
10A	3/30/79	51	S	112	11.5	7.4	95	247	0.335	0.012	3.520	133	--	
10B	3/30/79	51	S	141	12.8	5.7	265	265	0.359	0.000	3.106	113	--	
10C	3/30/79	51	S	72	9.2	9.2	63	245	0.332	0.000	3.212	76	--	
10D	3/30/79	51	S	92	10.4	8.6	85	252	0.341	0.009	3.414	82	--	
10E	3/30/79	51	S	173	13.7	5.8	443	286	0.387	0.000	3.351	127	--	
11	4/04/79	100	S	75	9.4	9.2	197	353	0.478	0.000	3.398	112	--	SASS, SO_3

NOTE: Design Capacity of Boiler is 45,000 lb/hr Steam

S = Sands Hill Coal

OOS = Analyzer Out-of-Service

SO_3 = 33 ppm or 0.065 $lb/10^6Btu$ as SO_2 in Test 11

* All data expressed in parts-per-million (ppm) have been corrected to 3% O_2

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3.0 DESCRIPTION OF FACILITY TESTED AND COAL FIRED

This section discusses the general physical layout and operational characteristics of the boiler tested at Test Site H. The coal utilized at this test site is also discussed.

3.1 BOILER H DESCRIPTION

Boiler H is a Bros boiler designed for 200 psig and capable of a maximum continuous capacity of 45,000 pounds of steam per hour at 140 psig and saturated temperature.

The unit has a Harrington traveling grate stoker manufacturer by Riley Stoker Company. Coal is added to the boiler by using a weigh lorry and is mass fired at the front of the grate. Ash is continuously discharged into a pit at the end of the grate. There is no suspension burning. Undergrate air can be controlled in four zones. This unit has no dust collector and no flyash reinjection. Design data for this unit is presented in Table 3-1.

3.2 OVERFIRE AIR SYSTEM

The overfire air system on Boiler H consists of one row of 10 air jets on the front wall. The nozzles are 2-1/2 inches in diameter and are located 50 inches above the grate at a 45 degree angle. The normal overfire air pressure was found to be operating at about 3" H_2O. At maximum flow the pressure is about 12" H_2O.

3.3 TEST PORT LOCATIONS

Emissions measurements were made at the stack. The location of the sampling plane is shown in Figure 3-1, and its geometry is shown in Figure 3-2.

TABLE 3-1

DESIGN DATA
TEST SITE H

BOILER:	Manufacturer	Bros
	Design Pressure	200 psig
	Boiler Heating Surface	5,780 ft^2
FURNACE:	Volume	1,850 ft^3
STOKER:	Manufacturer	Riley Stoker Company
	Type	Harrington Traveling Grate
	Width	13.0 ft
	Length	11.0 ft
	Effective Grate Area	140.25 ft^2
HEAT RATES:	Steam Flow	45,000 lb/hr
	Input to Furnace *	59.6 $x10^6$ Btu/hr
	Heat Available *	45.3 $x10^6$ Btu/hr
	Furnace Width Heat Release *	4.58 $x10^6$ Btu/ft-hr
	Grate Heat Release *	425 $x10^3$ Btu/ft^2-hr
	Furnace Liberation *	32.3 $x10^3$ Btu/ft^3-hr

*Heat rates were determined by KVB based on available information and are not necessarily those of the manufacturer.

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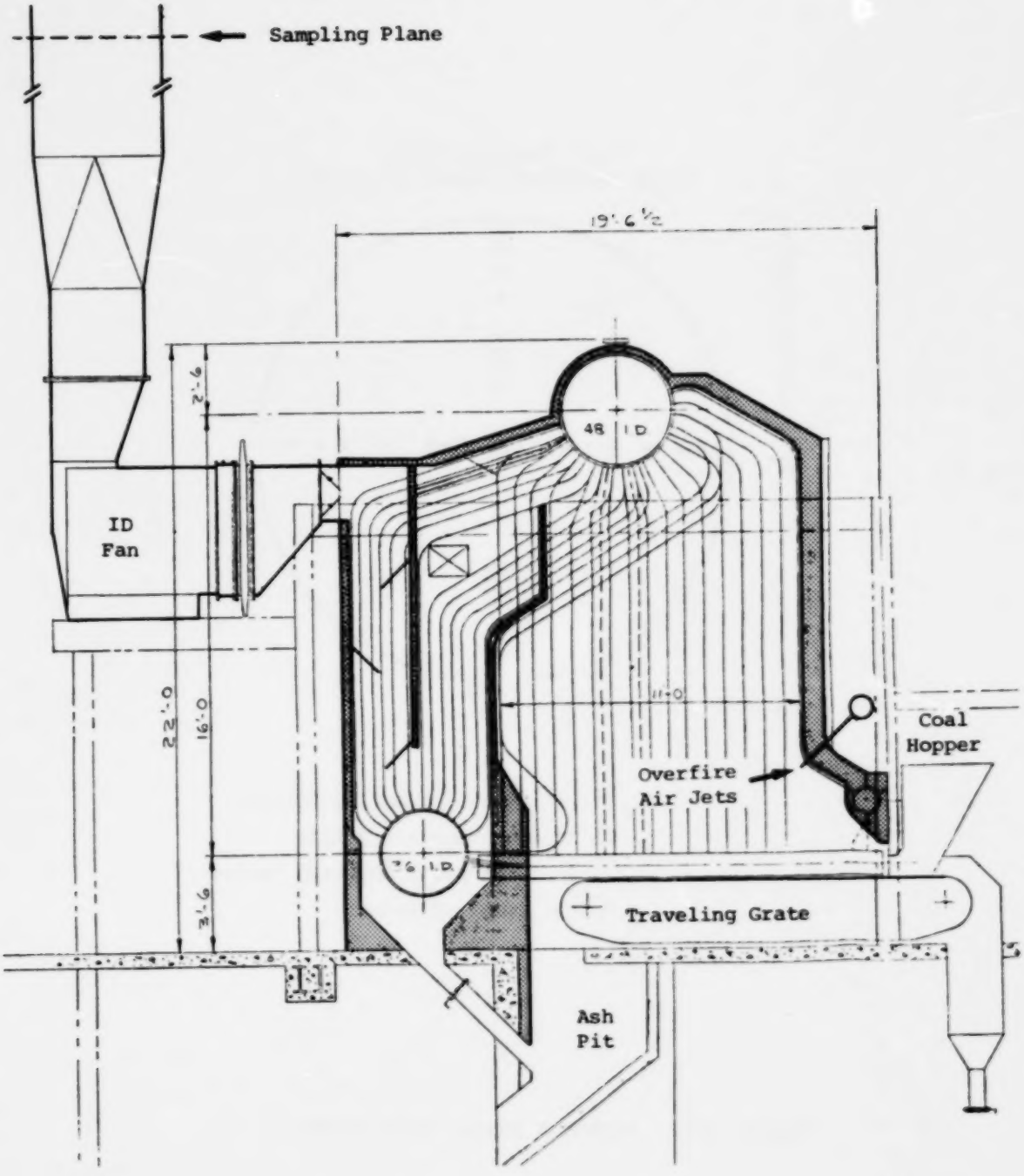

Figure 3-1. General Arrangement Drawing of Boiler H.

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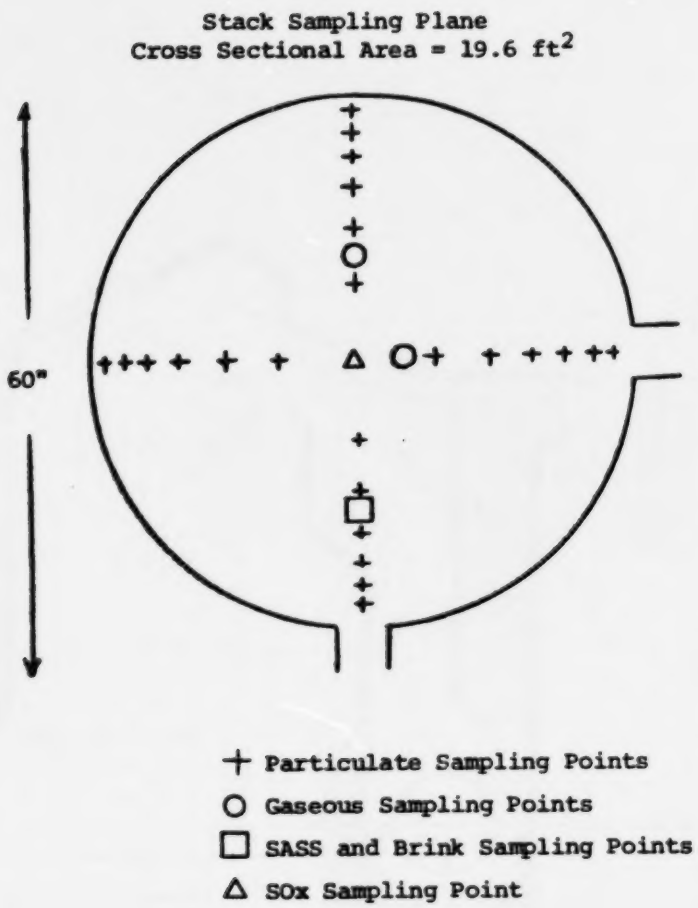
Stack Sampling Plane
Cross Sectional Area = 19.6 ft2
60"
+ Particulate Sampling Points
O Gaseous Sampling Points
□ SASS and Brink Sampling Points
Δ SOx Sampling Point

Figure 3-2. Boiler H Sample Plane Geometry

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Particulate loading was measured using a 24-point sample traverse. Gaseous measurements of O_2, CO_2, CO and NO were obtained by pulling samples individually and compositely from two probes. NO_2, SO_2 and unburned hydrocarbon measurements were made by sampling through a heated line attached to a probe. Its purpose was to eliminate losses due to condensation. SO_3 measurements and SASS samples for organic and trace element determinations were each obtained from single points.

3.4 COAL UTILIZED

One coal was tested at Test Site H. This coal is identified as Sands Hill coal as it is from the Sands Hill strip mine in Ohio. Coal samples were taken for each test involving particulates or SASS sampling. The average analyses obtained from these samples is presented in Table 3-2. Individual fuel analyses for each coal sampled are presented in Section 5.0, Test Results and Observations.

TABLE 3-2

AVERAGE COAL ANALYSIS
TEST SITE H

	SANDS HILL COAL
PROXIMATE (as Rec)	
% Moisture	11.56
% Ash	8.62
% Volatile	35.16
% Fixed Carbon	44.66
Btu/lb	11417
% Sulfur	1.88
ULTIMATE (as Rec)	
% Moisture	11.76
% Carbon	63.23
% Hydrogen	4.36
% Nitrogen	1.08
% Chlorine	0.07
% Sulfur	1.72
% Ash	8.93
% Oxygen	8.87
ASH FUSION (red)	
Initial Deformation	2205°F
Softening (H=W)	2363°F
Softening (H=1/2W)	2403°F
Fluid	2598°F

4.0 TEST EQUIPMENT AND PROCEDURES

This section details how specific emissions were measured and describes the sampling procedures followed to assure that accurate, reliable data were collected.

4.1 GASEOUS EMISSIONS MEASUREMENTS (NOx, CO, CO_2, O_2, HC, SO_2)

A description is given below of the analytical instrumentation, related equipment, and the gas sampling and conditioning system, all of which are located in a mobile testing van owned and operated by KVB. The systems have been developed as a result of testing since 1970, and are operational and fully checked out.

4.1.1 Analytical Instruments and Related Equipment

The analytical system consists of five instruments and associated equipment for simultaneously measuring the constituents of flue gas. The analyzers, recorders, valves, controls, and manifolds are mounted on a panel in the vehicle. The analyzers are shock mounted to prevent vibration damage. The flue gas constituents which are measured are oxides of nitrogen (NO, NOx), carbon monoxide (CO), carbon dioxide (CO_2), oxygen (O_2), gaseous hydrocarbons (HC), and sulfur dioxide (SO_2).

Listed below are the measurement parameters, the analyzer model furnished, and the range and accuracy of each parameter for the system. A detailed discussion of each analyzer follows:

Constituent:	Nitric Oxide/Total Oxides of Nitrogen (NO/NOx)
Analyzer:	Thermo Electron Model 10 Chemiluminescent Analyzer
Range:	0-2.5, 10, 25, 100, 250, 1000, 2500, 10,000 ppm NO
Accuracy:	±1% of full scale

Constituent:	Carbon Monoxide
Analyzer:	Beckman Model 315B NDIR Analyzer
Range:	0-500 and 0-2000 ppm CO
Accuracy:	±1% of full scale

Constituent:	Carbon Dioxide
Analyzer:	Beckman Model 864 NDIR Analyzer
Range:	0-5% and 0-20% CO_2
Accuracy:	±1% of full scale
Constituent:	Oxygen
Analyzer:	Teledyne Model 326A Fuel Cell Analyzer
Range:	0-5, 10, and 25% O_2 full scale
Accuracy:	±1% of full scale
Constituent:	Hydrocarbons
Analyzer:	Beckman Model 402 Flame Ionization Analyzer
Range:	5 ppm full scale to 10% full scale
Accuracy:	±1% of full scale
Constituent:	Sulfur Dioxide
Analyzer:	Dupont Model 400 Photometric Analyzer
Range:	0-200 ppm and 0-2000 ppm
Accuracy:	±1% of reading plus ±1/4% of full scale range

Oxides of Nitrogen. The instrument used to monitor oxides of nitrogen is a Thermo Electron chemiluminescent nitric oxide analyzer. The instrument operates by measuring the chemiluminescent reaction of NO and O_3 to form NO_2. Light is emitted when electronically excited NO_2 molecules revert to their ground state. The resulting chemiluminescence is monitored through an optical filter by a high sensitivity photomultiplier, the output of which is linearly proportional to the NO concentration.

Air for the ozonator is drawn from ambient air through a dryer and a ten micrometer filter element. Flow control for the instrument is accomplished by means of a small bellows pump mounted on the vent of the instrument downstream of a separator that prevents water from collecting in the pump.

The basic analyzer is sensitive only to NO molecules. To measure NOx (i.e., $NO+NO_2$), the NO_2 is first converted to NO. This is accomplished by a converter which is included with the analyzer. The conversion occurs as the gas passes through a thermally insulated, resistance heated, stainless steel coil. With the application of heat, NO_2 molecules in the sample gas are reduced to NO molecules, and the analyzer now reads NOx. NO_2 is obtained by the difference in readings obtained with and without the converter in operation.

Specifications: Accuracy 1% of full scale
Span stability ±1% of full scale in 24 hours
Zero stability ±1 ppm in 24 hours
Power requirements 115±10V, 60 Hz, 1000 watts
Response 90% of full scale in 1 sec. (NOx mode),
0.7 sec. NO mode
Output 4-20 ma
Sensitivity 0.5 ppm
Linearity ±1% of full scale
Vacuum detector operation
Range: 2.5, 10, 25, 100, 250, 1000, 2500, 10,000 ppm full scale

Carbon Monoxide. Carbon monoxide concentration is measured by a Beckman 315B non-dispersive infrared analyzer. This instrument measures the differential in infrared energy absorbed from energy beams passed through a reference cell (containing a gas selected to have minimal absorption of infrared energy in the wavelength absorbed by the gas component of interest) and a sample cell through which the sample gas flows continuously. The differential absorption appears as a reading on a scale from 0 to 100 and is then related to the concentration of the specie of interest by calibration curves supplied with the instrument. The operating ranges for the CO analyzer are 0-500 ppm and 0-2000 ppm.

Specifications: Span stability ±1% of full scale in 24 hours
Zero stability ±1% of full scale in 24 hours
Ambient temperature range 32°F to 120°F
Line voltage 115±15V rms
Response 90% of full scale in 0.5 or 2.5 sec.
Precision ±1% of full scale
Output 4-20 ma

Carbon Dioxide. Carbon dioxide concentration is measured by a Beckman Model 864 short path-length, non-dispersive infrared analyzer. This instrument measures the differential in infrared energy absorbed from energy beams passed through a reference cell (containing a gas selected to have minimal absorption of infrared energy in the wavelength absorbed by the gas component of interest) and a sample cell through which the sample gas flows continuously. The differential absorption appears as a reading on a scale from 0 to 100 and is then related to the concentration of the specie of interest by calibration curves supplied with the instrument. The operating ranges for the CO_2 analyzer are 0-5% and 0-20%.

Specifications: Span stability ±1% of full scale in 24 hours
Zero stability ±1% of full scale in 24 hours
Ambient temperature range 32°F to 120°F
Line voltage 115±15V rms
Response 90% of full scale in 0.5 or 2.5 sec.
Precision ±1% of full scale
Output 4-20 ma

Oxygen. The oxygen content of the flue gas sample is automatically and continuously determined with a Teledyne Model 326A Oxygen analyzer. Oxygen in the flue gas diffuses through a Teflon membrane and is reduced on the surface of the cathode. A corresponding oxidation occurs at the anode internally and an electric current is produced that is proportional to the concentration of oxygen. This current is measured and conditioned by the instrument's electronic circuitry to give a final output in percent O_2 by volume for operating ranges of 0% to 5%, 0% to 10%, or 0% to 25%.

Specifications: Precision ±1% of full scale
Response 90% in less than 40 sec.
Sensitivity 1% of low range
Linearity ±1% of full scale
Ambient temperature range 32-125°F
Fuel cell life expectancy 40,000%-hours
Power requirement 115 VAC, 50-60 Hz, 100 watts
Output 4-20 ma

Hydrocarbons. Hydrocarbons are measured using a Beckman Model 402 hydrocarbon analyzer which utilizes the flame ionization method of detection. The sample is drawn to the analyzer through a heated line to prevent the loss of higher molecular weight hydrocarbons. It is then filtered and supplied to the burner by means of a pump and flow control system. The sensor, which is the burner, has its flame sustained by regulated flows of fuel (40% hydrogen plus 60% helium) and air. In the flame, the hydrocarbon components of the sample undergo a complete ionization that produces electrons and positive ions. Polarized electrodes collect these ions, causing a small current to flow through a circuit. This ionization current is proportional to the concentration of hydrocarbon atoms which enter the burner. The instrument is available with range selection from 5 ppm to 10% full scale as CH_4.

Specifications: Full scale sensitivity, adjustable from 5 ppm CH_4 to 10% CH_4
Ranges: Range multiplier switch has 8 positions: X1, X5, X10, X50, X100, X500, X1000, and X5000. In addition, span control provides continuously variable adjustment within a dynamic range of 10:1
Response time 90% full scale in 0.5 sec.
Precision ±1% of full scale
Electronic stability ±1% of full scale for successive identical samples
Reproducibility ±1% of full scale for successive identical samples
Analysis temperature: ambient
Ambient temperature 32°F to 110°F
Output 4-20 ma
Air requirements 350 to 400 cc/min of clean, hydrocarbon-free air, supplied at 30 to 200 psig
Fuel gas requirements 75 to 80 cc/min of pre-mixed fuel consisting of 40% hydrogen and 60% nitrogen or helium, supplied at 30 to 200 psig
Electrical power requirements 120V, 60 Hz
Automatic flame-out indication and fuel shut-off valve

Sulfur Dioxide. Sulfur dioxide is measured by a Dupont Model 400 photometric analyzer. This analyzer measures the difference in absorption of two distinct wavelengths (ultraviolet) by the sample. The radiation from a selected light source passes through the sample and then into the photometer unit where the radiation is split by a semi-transparent mirror into two beams. One beam is directed to a phototube through a filter which removes all wavelengths except the "measuring" wavelength. which is strongly absorbed by the constituent in the sample. A second beam falls on a reference phototube, after passing through an optical filter which transmits only the "reference" wavelength. The latter is absorbed only weakly, or not at all, by the constituent in the sample cell. The phototubes translate these intensities to proportional electric currents in the amplifier. In the amplifier, full correction is made for the logarithmic relationships between the ratio of the intensities and concentration or thickness (in accordance with Beer's Law). The output is, therefore, linearly proportional, at all times, to the concentration and thickness of the sample. The instrument has a lower detection limit of 2 ppm and full scale ranges of 0-200 and 0-2000 ppm.

Specifications: Noise less than 1/4%
Drift less than 1% full scale in 24 hours

Accuracy (±1% of analyzer reading)+(±1/4% of full scale range)
Sample cell 304 stainless steel, quartz windows
Flow rate 6 CFH
Light source is mercury vapor, tungsten, or "Osram" discharge type lamps
Power rating 500 watts maximum, 115 V, 60 Hz
Reproducibility 1/4% of scale
Electronic response 90% in 1 sec
Sample temperature 378 K (220°F)
Output 4-20 ma d.c.

4.1.2 Gas Sampling and Conditioning System

A flow schematic of the flue gas sampling and analysis system is shown in Figure 4-1. The sampling system uses 3 positive displacement diaphragm pumps to continuously draw flue gas from the stack into the laboratory. The sample pumps pull from 6 unheated sample lines. Selector valves allow composites of up to 6 points to be sampled at one time. The probes are connected to the sample pumps with 0.95 cm (3/8") or 0.64 cm (1/4") nylon line. The positive displacement diaphrahm sample pumps provide unheated sample gas to the refrigerated condenser (to reduce the dew point to 35°F), a rotameter with flow control valve, and to the O_2, NO, CO, and CO_2 instrumentation. Flow to the individual analyzers is measured and controlled with rotameters and flow control valves. Excess sample is vented to the atmosphere.

To obtain a representative sample for the analysis of NO_2, SO_2 and hydrocarbons, the sample must be kept above its dew point, since heavy hydrocarbons may be condensible and SO_2 and NO_2 are quite soluble in water. For this reason, a separate, electrically-heated, sample line is used to bring the sample into the laboratory for analysis. The sample line is 0.64 cm (1/4-inch) Teflon line, electrically traced and thermally insulated to maintain a sample temperature of up to 400°F. Metal bellows pumps provide sample to the hydrocarbon, SO_2 and NOx analyzers.

4.1.3 Continuous Measurements

The laboratory trailer is equipped with analytical instruments to continuously measure concentrations of NO, NO_2, CO, CO_2, O_2, SO_2, and hydrocarbons. All of the continuous monitoring instruments and sample handling

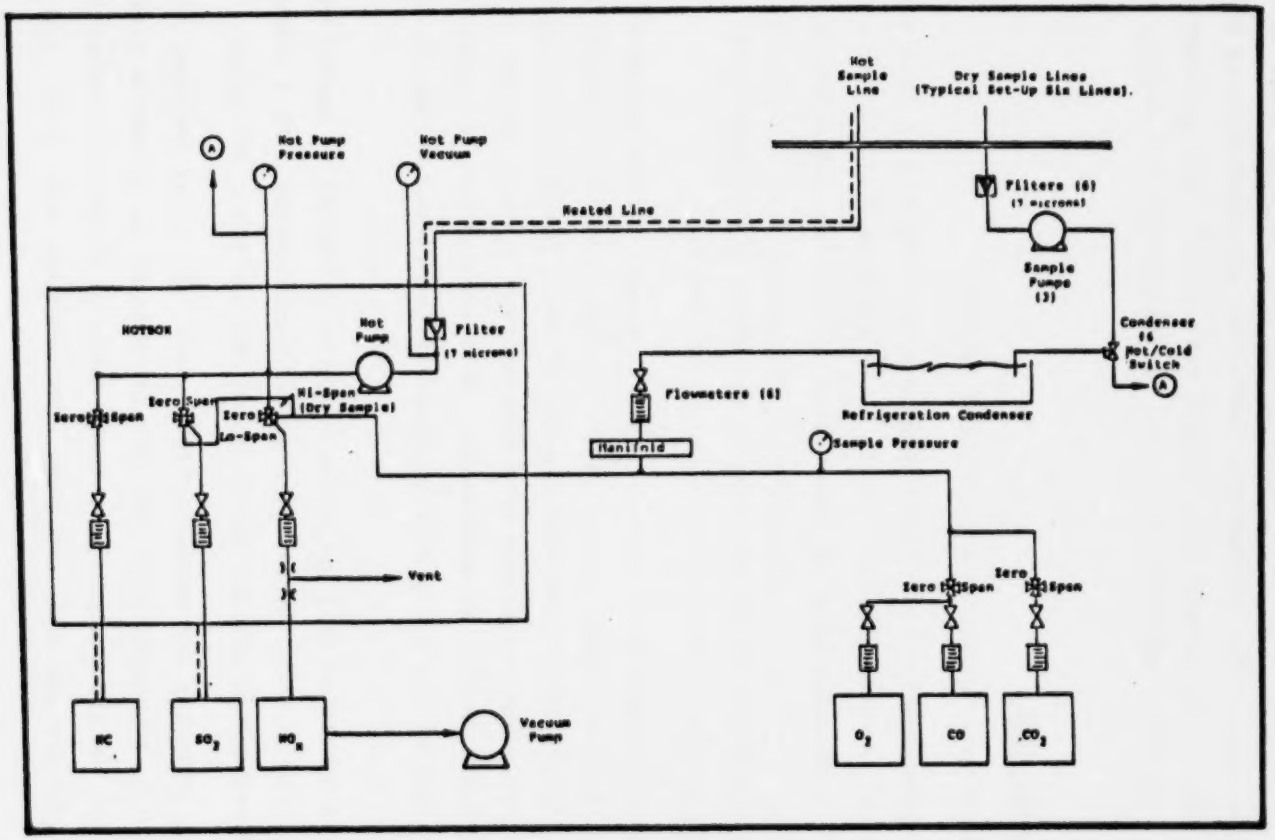

Figure 4-1. Flue Gas Sampling and Analyzing System

system are mounted in the self-contained mobile laboratory. The entire system requires only connection to on-site water, power, and sampling lines to become fully operational. The instruments themselves are shock mounted on a metal console panel. The sample flow control measurement, and selection, together with instrument calibration are all performed from the console face.

4.2 SULFUR OXIDES (SOx)

Goksoyr-Ross Method -- Wet Chemical Method

The Goksoyr-Ross Controlled Condensate (G/R) method is used for the wet chemical SO_2/SO_3 determination. It is a desirable method because of its simplicity and clean separation of particulate matter, SO_2 and H_2SO_4 (SO_3). This procedure is based on the separation of $H_2SO_4(SO_3)$ from SO_2 by cooling the gas stream below the dew point of H_2SO_4 but above the H_2O dew point. Figure 4-2 illustrates schematically the G/R test system.

Particulate matter is first removed from exhaust gas stream by means of a quartz glass filter placed in the heated glass filter holder. Tissue-quartz filters are recommended because of their proven inertness to H_2SO_4. The filter system is heated by a heating tape so that the gas out temperature of 260°C (500°F) is maintained. This temperature is imperative to ensure that none of the H_2SO_4 will condense in the filter holder or on the filter.

The condensation coil where the H_2SO_4 is collected is cooled by water which is maintained at 60°C (140°F) by a heater/recirculator. This temperature is adequate to reduce the exhaust gas to below the dew point of H_2SO_4.

Three impingers are shown in Figure 4-2. The first impinger is filled with 3% H_2O_2 to absorb SO_2. The second impinger is to remove carry over moisture and the third contains a thermometer to measure the exhaust gas temperature to the dry gas meter and pump. The sampling rate is 2.3 lpm (0.08 CFM).

For both SO_2 and H_2SO_4 determination, the analytical procedure is identical. The H_2SO_4 sample is washed from the back part of the filter holder and the coil using distilled water. The sample from the first impinger which is assumed to be absorbed and reacted SO_2 in the form of H_2SO_4 is recovered with distilled water washing. The amount of H_2SO_4 in the condensate from the coil and from the H_2O_2 impinger is measured by H+ titration. Bromphenol Blue is used with NaOH as the titrant.

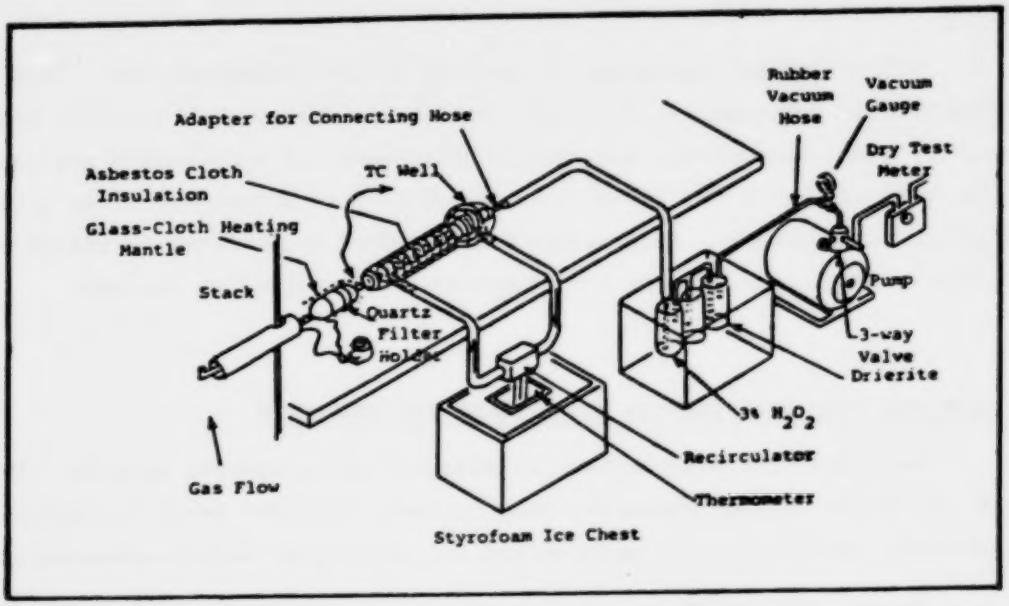

Figure 4-2. Schematic of Goksoyr-Ross Controlled Condensation System (CCS).

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4.3 PARTICULATE MEASUREMENT AND PROCEDURES

Particulate samples are taken at the same sample ports as the gaseous emission samples using a Joy Manufacturing Company portable effluent sampler (Figure 4-3). This system, which meets the EPA design specifications for Test Method 5, Determination of Particulate Emissions from Stationary Sources (Federal Register, Volume 36, No. 27, page 24888, December 23, 1971), is used to perform both the initial velocity traverse and the particulate sample collection. Dry particulates are collected in a heated case using first a cyclone to separate particles larger than five micrometers and a 100 mm glass fiber filter for retention of particles down to 0.3 micrometers. Condensible particulates are collected in a train of four Greenburg-Smith impingers in an ice water bath. The control unit includes a total gas meter and thermocouple indicator. A pitot tube system is provided for setting sample flows to obtain isokinetic sampling conditions.

All peripheral equipment is carried in the instrument van. This includes a scale (accurate to $\pm$0.1 mg), hot plate, drying oven (212°F), high temperature oven, desiccator, and related glassware. A particulate analysis laboratory is set up in the vicinity of the boiler in a vibration-free area. Here filters are prepared, tare weighed and weighed again after particulate collection. Also, probe washes are evaporated and weighed in the lab.

4.4 PARTICLE SIZE DISTRIBUTION MEASUREMENT AND PROCEDURE

Particle size distribution is measured using several methods. These include the Brink Cascade Impactor, SASS cyclones, and the Bahco Classifier. Each of these particle sizing methods has its advantages and disadvantages.

Brink. The Brink cascade impactor is an in-situ particle sizing device which separates the particles into six size classifications. It has the advantage of collecting the entire sample. That is, everything down to the collection efficiency of the final filter is included in the analysis. It has, however, some disadvantages. If the particulate matter is spatially stratified within the duct, the single-point Brink sampler will yield erroneous results. Unfortunately, the particles at the outlets of stoker boilers may be considerably stratified. Another disadvantage is the instrument's small classification

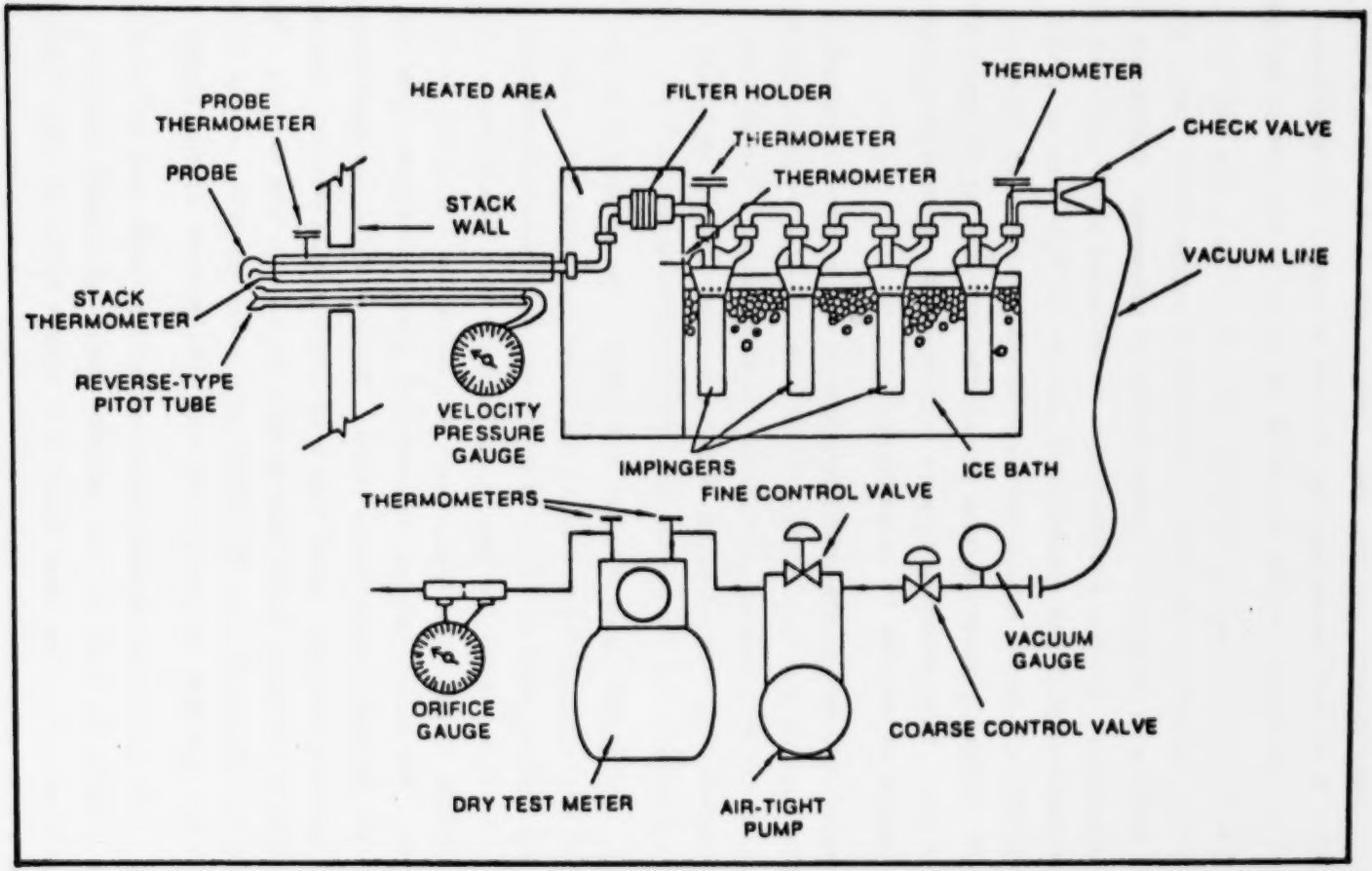

Figure 4-3. EPA Method 5 Particulate Sampling Train

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range (0.3 to 3.0 micrometers) and its small sample nozzle (1.5 to 2.0 mm maximum diamter). Both are inadequate for the job at hand. The particles being collected at the boiler outlet are often as large as the sample nozzle.

The sampling procedure is straight forward. First, the gas velocity at the sample point is determined using a calibrated S-type pitot tube. For this purpose a hand held particulate probe, inclined manometer, thermocouple and indicator are used. Second, a nozzle size is selected which will maintain isokinetic flow rates within the recommended .02-.07 ft^3/min rate at stack conditions. Having selected a nozzle and determined the required flow rate for isokinetics, the operating pressure drop across the impactor is determined from a calibration curve. This pressure drop is corrected for temperature, pressure and molecular weight of the gas to be sampled.

A sample is drawn at the predetermined ΔP for a time period which is dictated by mass loading and size distribution. To minimize weighing errors, it is desirable to collect several milligrams on each stage. However, to minimize reentrainment, a rule of thumb is that no stage should be loaded above 10 mg. A schematic of the Brink sampling train is shown in Figure 4-4.

Bahco. The Bahco classifier is described in Power Test Code 28. It is an acceptable particle sizing method in the power industry and is often used in specifying mechanical dust collector guarantees. Its main disadvantage is that it is only as accurate as the sample collected. Most Bahco samples are collected by cyclone separation; thus, particles below the cut point of the cyclone are lost. The Bahco samples collected at Test Site F came from the cyclone in the EPA Method 5 particulate train. These samples are spatially representative because they are taken from a 12-point sample matrix. However, much of the sample below about seven micrometers is lost to the filter. The Bahco test data are presented in combination with sieve analysis of the same sample. An attempt was made to correct for the lost portion of the sample.

SASS. The Source Assessment Sampling System (SASS) was not designed principally as a particle sizer but it includes three calibrated cyclones which can be used as such. The SASS train is a single point in-situ sampler. Thus, it is on a part with cascade impactors. Because it is a high volume sampler and samples are drawn through large nozzles (0.25 to 1.0 in.), it has

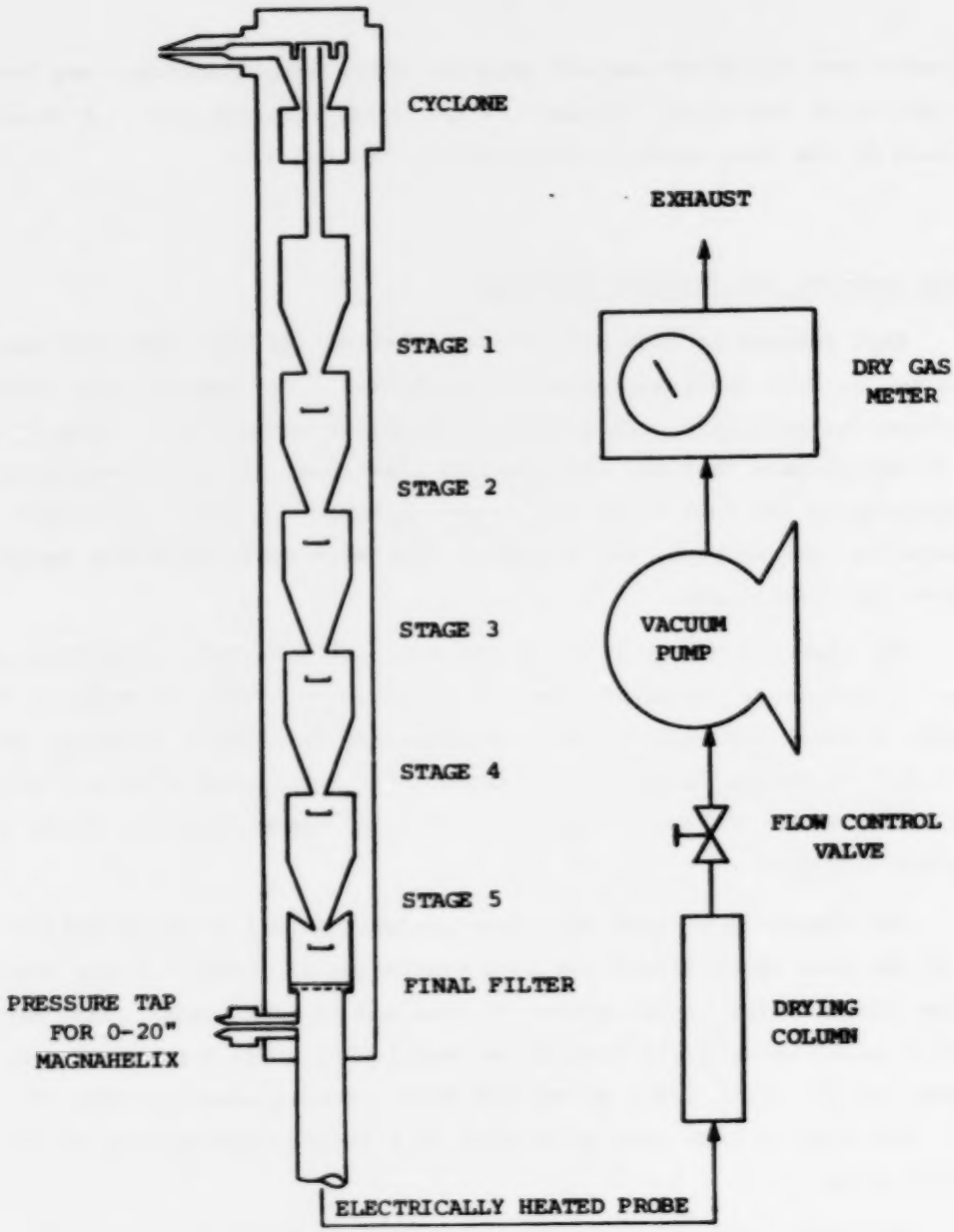

Figure 4-4. Brink Cascade Impactor Sampling Train Schematic

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an advantage over the Brink cascade impactor where large particles are involved. The cut points of the three cyclones are 10, 3 and 1 micrometers. A detailed description of the SASS train is presented in Section 4.8.

4.5 COAL SAMPLING AND ANALYSIS PROCEDURE

Coal samples at Test Site H were taken during each test from the weigh lorry, as coal was being added to the boiler. The samples were processed and analyzed for both size consistency and chemical composition. This is close enough to the furnace that the coal sampled simultaneously with testing is representative of the coal fired during the testing. In order to collect representative coal samples, ten pounds of coal were taken from each batch added from the weigh lorry.

The sampling procedure is as follows. At the start of testing one increment of sample is collected from the weigh lorry. This is repeated for each batch of coal added during the test (three to five hours duration) so that a 7 to 12 increment sample is obtained. The total sample is then riffled using a Gilson Model SP-2 Porta Splitter until two representative twenty point samples are obtained.

The sample to be used for sieve analysis is air dried overnight. Drying of the coal is necessary for good separation of fines. If the coal is wet, fines cling to the larger pieces of coal and to each other. Once dry, the coal is sized using a six tray Gilson Model PS-3 Porta Screen. Screen sizes used are 1", 1/2", 1/4", #8 and #16 mesh. Screen area per tray is 14"x14". The coal in each tray is weighed on a triple beam balance to the nearest 0.1 gram.

The coal sample for chemical analysis is reduced to 2-3 pounds by further riffling and sealed in a plastic bag. All coal samples are sent to Commercial Testing and Engineering Company, South Holland, Illinois. Each sample associated with a particulate loading or particle sizing test is given a proximate analysis. In addition, composite samples consisting of one increment of coal for each test for each coal type receive ultimate analysis, ash fusion temperature, mineral analysis, Hardgrove grindability and free swelling index measurements.

4.6 ASH COLLECTION AND ANALYSIS FOR COMBUSTIBLES

The combustible content of flyash is determined in the field by KVB in accordance with ASTM D3173, "Moisture in the Analysis Sample of Coal and Coke" and ASTM D3174, "Ash in the Analysis Sample of Coal and Coke."

The flyash sample is collected by the EPA Method 5 particulate sample train while sampling for particulates. The cyclone catch is placed in a desiccated and tare-weighed ceramic crucible. The crucible with sample is heated in an oven at 230°F to remove its moisture. It is then desiccated to room temperature and weighed. The crucible with sample is then placed in an electric muffle furnace maintained at a temperature of 1400°F until ignition is complete and the sample has reached a constant weight. It is cooled in a desiccator over desiccant and weighed. Combustible content is calculated as the percent weight loss of the sample based on its post 230°F weight.

At Test Site H the bottom ash samples were collected in several increments from the ash pit, after testing. These samples were mixed, quartered, and sent to Commercial Testing and Engineering Company for combustible determination.

4.7 BOILER EFFICIENCY EVALUATION

Boiler efficiency is calculated using the ASME Test Form for Abbreviated Efficiency Test, Revised, September, 1965. The general approach to efficiency evaluation is based on the assessment of combustion losses. These losses can be grouped into three major categories: stack gas losses, combustible losses, and radiation losses. The first two groups of losses are measured directly. The third is estimated from the ABMA Standard Radiation Loss Chart.

Unlike the ASME test in which combustible losses are lumped into one category, combustible losses are calculated and reported separately for combustibles in the bottom ash, and combustibles in the flyash leaving the boiler.

4.8 TRACE SPECIES MEASUREMENT

The EPA (IERL-RTP) has developed the Source Assessment Sampling System (SASS) train for the collection of particulate and volatile matter in addition to gaseous samples (Figure 4-5). The "catch" from the SASS train is analyzed for polynuclear aromatic hydrocarbons (PAH) and inorganic trace elements.

In this system, a stainless steel heated probe is connected to an oven module containing three cyclones and a filter. Size fractionation is accomplished in the series cyclone portion of the SASS train, which incorporates the cyclones in series to provide large quantities of particulate matter which are classified by size into three ranges:

A) >10 μm B) 3 μm to 10 μm C) 1 μm to 3 μm

Together with a filter, a fourth cut (<1 μm) is obtained. Volatile organic material is collected in an XAD-2 sorbent trap. The XAD-2 trap is an integral part of the gas treatment system which follows the oven containing the cyclone system. The gas treatment system is composed of four primary components: the gas conditioner, the XAD-2 organic sorbent trap, the aqueous condensate collector, and a temperature controller. The XAD-2 sorbent is a porous polymer resin with the capability of absorbing a broad range of organic species. Some trapping of volatile inorganic species is also anticipated as a result of simple impaction. Volatile inorganic elements are collected in a series of impingers. The pumping capacity is supplied by two 10 cfm high volume vacuum pumps, while required pressure, temperature, power and flow conditions are obtained from a main controller.

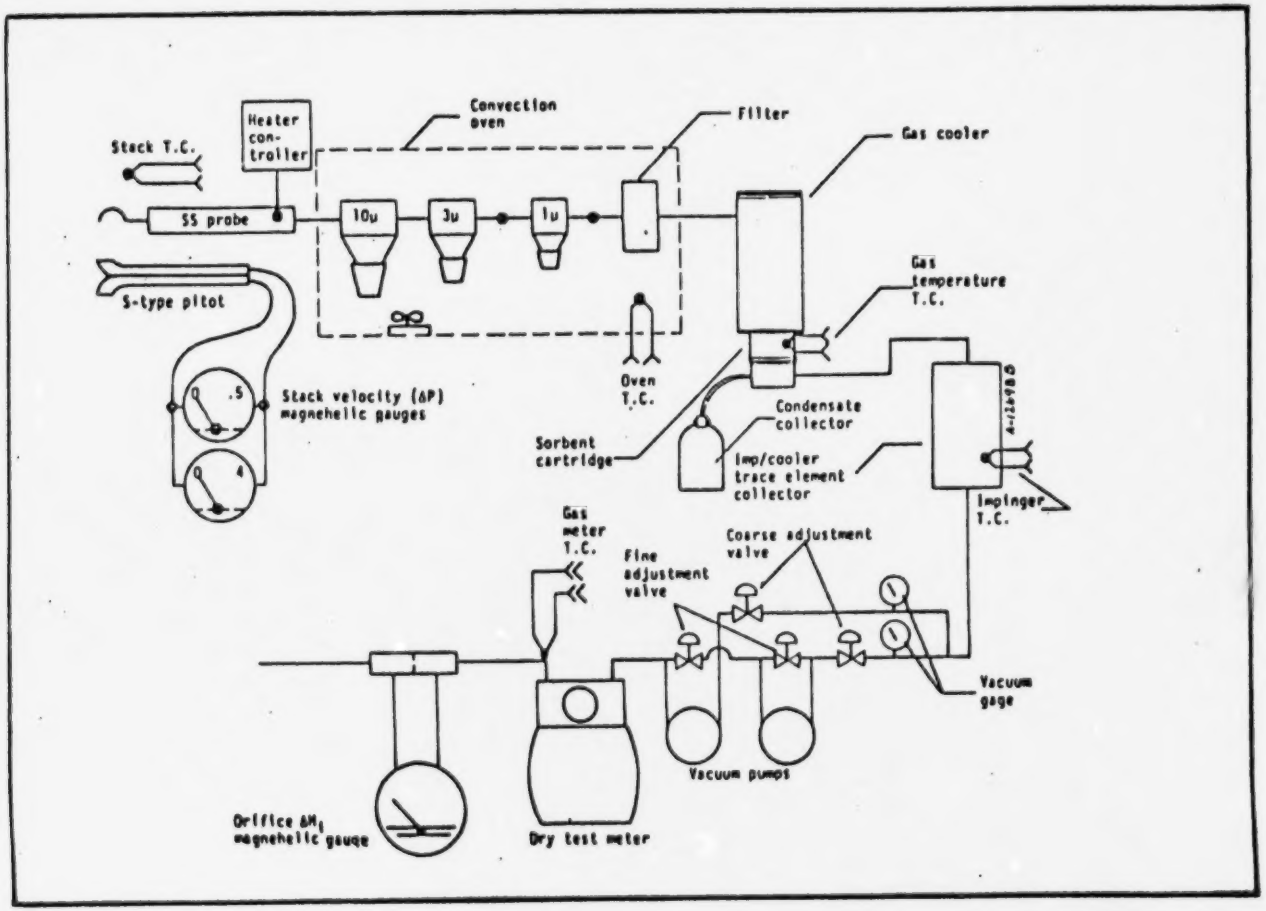

Figure 4-5. Source Assessment Sampling (SASS) Flow Diagram

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5.0 TEST RESULTS AND OBSERVATIONS

This section presents the results of tests performed on Boiler H. Observations are made regarding the influence on efficiency and on gaseous and particulate emissions as the control parameters are varied. Eleven defined tests were conducted over a two and one-half week period to develop this data. In addition to the many tables and figures presented in this section, reference may be made to Tables 2-1 and 2-2 in the Executive Summary, and to Tables 5-18 through 5-21 at the end of this section.

5.1 OVERFIRE AIR

Boiler H has an overfire air (OFA) system consisting of a single row of air jets along the front water wall just above the arch. Air flow to these jets is controlled manually. Upon arrival at the test site, it was discovered that the normal operating procedure was to leave the overfire air set at between 2.4 and 3.0 inches water pressure at all boiler loads. The operators of this unit believe that the low overfire air setting results in a higher boiler efficiency and reduced clinkering. This low overfire air setting was used as the "norm" or baseline condition in these tests.

During Test 4, the overfire air flow rate (lb/hr) was measured and related to static pressure in the overfire air duct. During Tests 5 and 6 the overfire air pressure was increased to 11.7 and 11.2 inches water pressure, respectively.

The general conclusion was that high overfire air pressure is the desirable mode of operation on this boiler at full steaming capacity. It was determined that the overfire air system on this boiler supplies 12% of the actual combustion air at full load (8% O_2 and 11.5" H_2O overfire air pressure). The test data are summarized in Table 5-1 and discussed in the following subsections.

5.1.1 Particulate Loading vs Overfire Air

The data show a 50% reduction in particulate loading when the overfire air pressure was increased from 2.7 to 11.7" H_2O while maintaining under-

TABLE 5-1

EFFECT OF OVERFIRE AIR ON EMISSIONS AND EFFICIENCY
TEST SITE H

Test No.	3	5	6
Description	Low OFA	High OFA	High OFA
FIRING CONDITIONS			
Load, % of Capacity	102	99	97
Grate Heat Release, 10^3Btu/hr-ft^2	432	421	413
Coal Fines, % Passing 1/4"	37	24	23
Excess Air, %	58	76	97
Overfire Air Pressure, "H_2O	2.7	11.7	11.2
BOILER EMISSIONS			
Particulate Loading, lb/10^6Btu	2.195	1.130	0.897
Combustible Loading, lb/10^6Btu	--	0.260	0.226
Inorganic Ash Loading, lb/10^6Btu	--	0.870	0.671
Combustibles in Flyash, %	--*	23.0	25.2
O_2, % (dry)	8.0	9.4	10.6
CO_2, % (dry)	10.8	9.2	9.1
CO, ppm (dry) @ 3% O_2	513	41	69
NO, lb/10^6Btu	0.371	0.459	0.448
NO_2, lb/10^6Btu	0.018	0.001	0.012
SO_2, lb/10^6Btu	2.617	3.524	3.378
HEAT LOSSES, %			
Dry Gas	12.77	13.93	13.85
Moisture in Fuel	1.14	1.43	1.45
H_2O from Combustion of H_2	4.17	4.31	4.40
Combustibles in Flyash	0.87*	0.37	0.32
Combustibles in Bottom Ash	1.54	2.52	2.67
Radiation	0.64	0.65	0.67
Unmeasured	1.50	1.50	1.50
Total Losses	22.63	24.71	24.86
Boiler Efficiency	77.37	75.29	75.14

*Test 3 flyash was sent to a laboratory for Bahco size classification and was available in insufficient quantity for both Bahco and combustibles determination. 28% combustibles in flyash was assumed.

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grate air flow constant. It is believed that at least some of the reduction in particulate mass loading was due to more complete carbon burnout of the flyash, but combustible data are not available to confirm this belief. The particulate vs overfire air test data are shown in Table 5-2.

TABLE 5-2

PARTICULATE LOADING VS OVERFIRE AIR

Test No.	Overfire Air	Particulate Loading $lb/10^6$ Btu
3	Low - 2.7" H_2O	2.20
5	High - 11.7" H_2O	1.13
6	High - 11.2" H_2O	0.90

5.1.2 Nitric Oxide vs Overfire Air

Nitric oxide emissions did not change as a function of overfire air. The test data, shown in Table 5-3, indicate that the low overfire air nitric oxide concentration is bracketed by the two high overfire air concentrations when corrections are made for differences in excess oxygen. The excess oxygen correction accounts for the fact that nitric oxide concentration increases by .055 $lb/10^6$ Btu for each one percent increase in oxygen on this boiler at full capacity (see Figure 5-6 in Section 5.2 for supporting data).

TABLE 5-3

NITRIC OXIDE VS OVERFIRE AIR

Test No.	Overfire Air	% O_2	Measured Nitric Oxide lb/10^6Btu	Nitric Oxide Corr to 8.0% O_2 lb/10^6Btu
3	Low - 2.7" H_2O	8.0	0.371	0.371
5	High - 11.7" H_2O	9.4	0.459	0.382
6	High - 11.2" H_2O	10.6	0.448	0.305

5.1.3 Carbon Monoxide and Unburned Hydrocarbon vs Overfire Air

The data indicate that increasing overfire air flow decreases both carbon monoxide and unburned hydrocarbon emissions. The two high overfire air tests produced the two lowest emission levels in both categories. The test data are presented in Table 5-4 (see Figure 5-12 and 5-14 in Section 5.2 for supporting data).

TABLE 5-4

CARBON MONOXIDE AND HYDROCARBON VS OVERFIRE AIR

Test No.	Overfire Air	Carbon Monoxide ppm @ 3% O_2 (dry)	Unburned Hydrocarbons ppm @ 3% O_2 (dry)
1A-B	Low - 2.4" H_2O	153-239	--
3	Low - 2.7" H_2O	513	--
2A-F	Low - 2.8" H_2O	96-712	--
11	Low - 3.0" H_2O	197	112
6	High - 11.2" H_2O	69	35
5	High - 11.7" H_2O	41	5

5.1.4 Boiler Efficiency vs Overfire Air

Boiler efficiency appears to decrease at high overfire air settings, but data are incomplete and factors other than overfire air are suspected to contribute to this effect. The data, shown in Table 5-5, show a measured two-percent decrease in boiler efficiency as overfire air is increased. One percent of this decrease is in the dry gas heat loss category, and is a result of the increased excess air. Another one percent of the decreased efficiency is in the bottom ash combustible category and it also may not be related to overfire air conditions. A better indicator of the effect of overfire air on boiler efficiency is the flyash combustible heat loss. Since data in this area are only estimated, no relationship was established.

TABLE 5-5

BOILER EFFICIENCY VS OVERFIRE AIR

Test No.	Overfire Air	SELECTED HEAT LOSSES			Boiler Efficiency, %
		Dry Gas	Bottom Ash Combustibles	Flyash Combustibles	
3	Low - 2.7" H_2O	12.77	1.54	0.87	77.37
5	High - 11.7" H_2O	13.93	2.52	0.37	75.29
6	High - 11.2" H_2O	13.85	2.67	0.32	75.14

5.1.5 Overfire Air Flow Rate

The rate at which air is injected into the furnace above the grate was measured using a standard pitot tube traverse of the overfire air duct. This measurement was made at three overfire air settings corresponding to 2.8, 7.2, and 11.2" H_2O. The 2.8" H_2O measurement data was discarded because excessive turbulence distorted the data. The results of the other two tests are believed to be reasonably accurate and are presented in Table 5-6.

The relationship between overfire air flow rate and overfire air pressure is plotted in Figure 5-1. Bernoulli's equation for fluid flow through an orifice is used in conjunction with the test data to create this relationship. Bernoulli's equation predicts that flow rate will be proportional to the square root of the pressure drop. This curve is adequate for predicting the overfire air flow rate on Boiler H at any overfire air pressure setting.

At 100% boiler capacity, 11.5 inches water pressure in the overfire air duct and 8% O_2, the overfire air system supplies 12% of the combustion air on Boiler H. This result is based on calculations indicating that 83,900 lb/hr air are required to burn Sands Hill coal at 8% O_2.

TABLE 5-6

OVERFIRE AIR FLOW RATE

Overfire Air Pressure "H_2O	Air Flow lb/hr	% Combustion Air Supplied by OFA @ 8% O_2 and 100% Capacity
11.2	10,240 (measured)	12.2
7.2	9,710 (measured)	11.6
2.8	5,530 (estimated)	6.6

5.2 EXCESS OXYGEN AND GRATE HEAT RELEASE

The boiler at Test Site H was tested for emissions and boiler efficiency at three boiler loadings representing 100%, 75% and 50% of design steaming capacity. At each load the boiler was tested over a wide range of excess air conditions. This section profiles the various emissions and the boiler efficiencies as a function of these two variables.

Boiler steam loading is expressed in terms of grate heat release. At full load, the grate heat release on this unit was 504,000 Btu/hr-ft^2. Excess air is expressed in terms of percent oxygen in the flue gas.

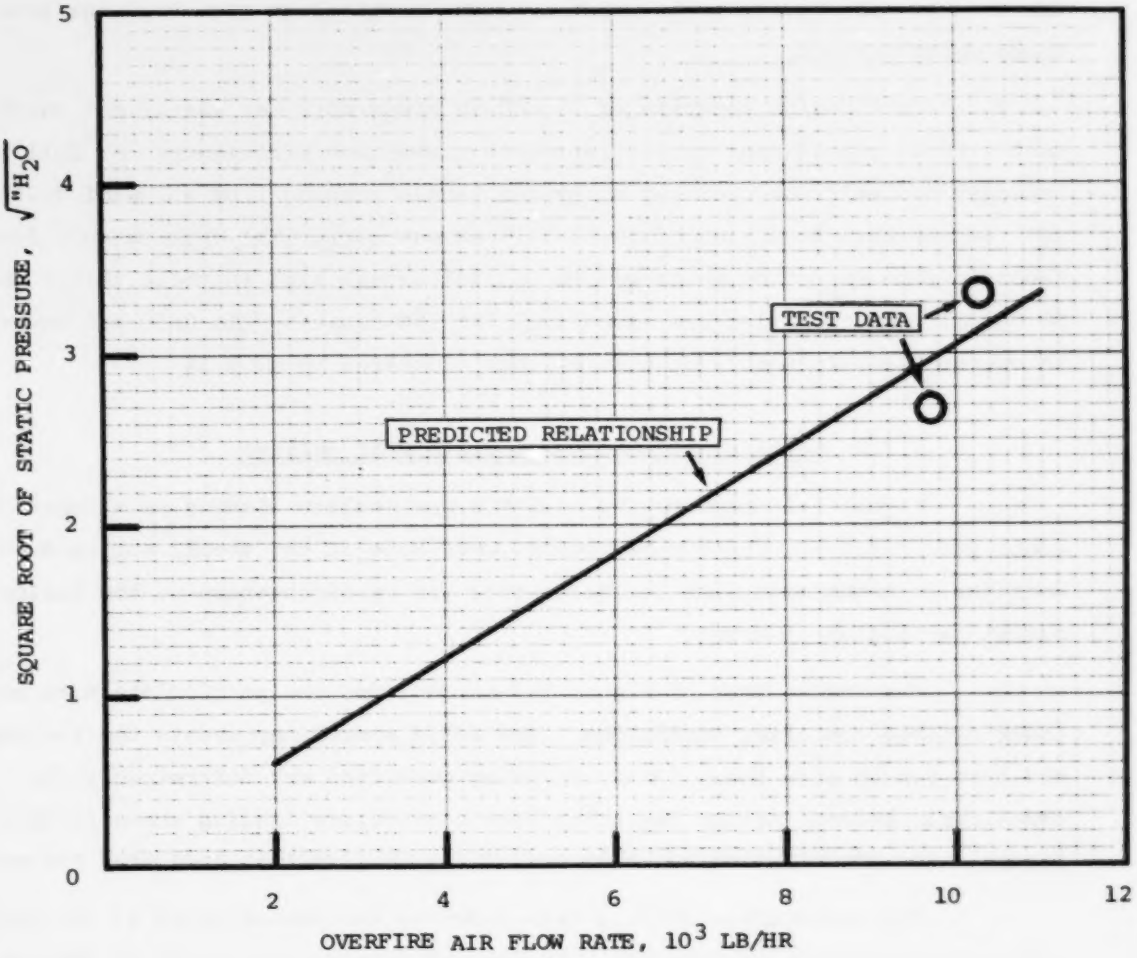

Figure 5-1. Relationship Between Overfire Air Flow Rate and Static Pressure Within the Overfire Air Duct - Test Site H.

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5.2.1 Excess Oxygen Operating Levels

Figure 5-2 depicts the various conditions of grate heat release and excess oxygen under which tests were run on the boiler at Site H. Solid symbols are used to distinguish tests which included particulate mass loadings from those which did not.

Full design capacity of 45,000 lb steam/hour was easily met on this unit without significant deterioration in combustion efficiency. At full capacity the unit was operated at oxygen levels ranging from a low of 7.2% (49% excess air) to a high of 10.6% (97% excess air). The optimum full load excess oxygen operating point was 8% O_2 (58% excess air) in these tests. Below 8% O_2, clinker formation was excessive. At 75% capacity the unit was observed to operate satisfactorily at 8.2% O_2, but clinkered up at 5.3% O_2.

5.2.2 Particulate Loading vs Grate Heat Release

Figure 5-3 presents the Boiler H particulate loading as a function of grate heat release. These measurements were made at the stack, but because the unit has no mechanical dust collector they are representative of the boiler outlet particulate loading.

The shaded area of Figure 5-3 encompasses the particulate data obtained under optimum operating conditions. The solid symbol represents the low overfire air test run at high load. This operating condition was determined to be undesirable because of the resulting high particulate loading shown in this figure. The uncontrolled variable coal fines (% <1/4") is indicated for each test.

The particulate loading data shows an increasing trend as the boiler load approaches 100% of capacity. At low and intermediate loads of 50% and 75% capacity, the particulate loading was 0.68 and 0.55 lb/10^6 Btu, respectively. However, at full load the particulate loading increased to 0.90 and 1.13 lb/10^6Btu.

The ash carryover was determined as the ratio of the ash leaving the boiler as flyash (with the combustible fraction subtracted out) and the ash entering the boiler with the coal. This data is presented in Table 5-7. The average ash carryover for the four optimum particulate tests was 7.0 ± 3.1%. The ash carryover for Test 3 could not be determined because its combustible fraction was unknown.

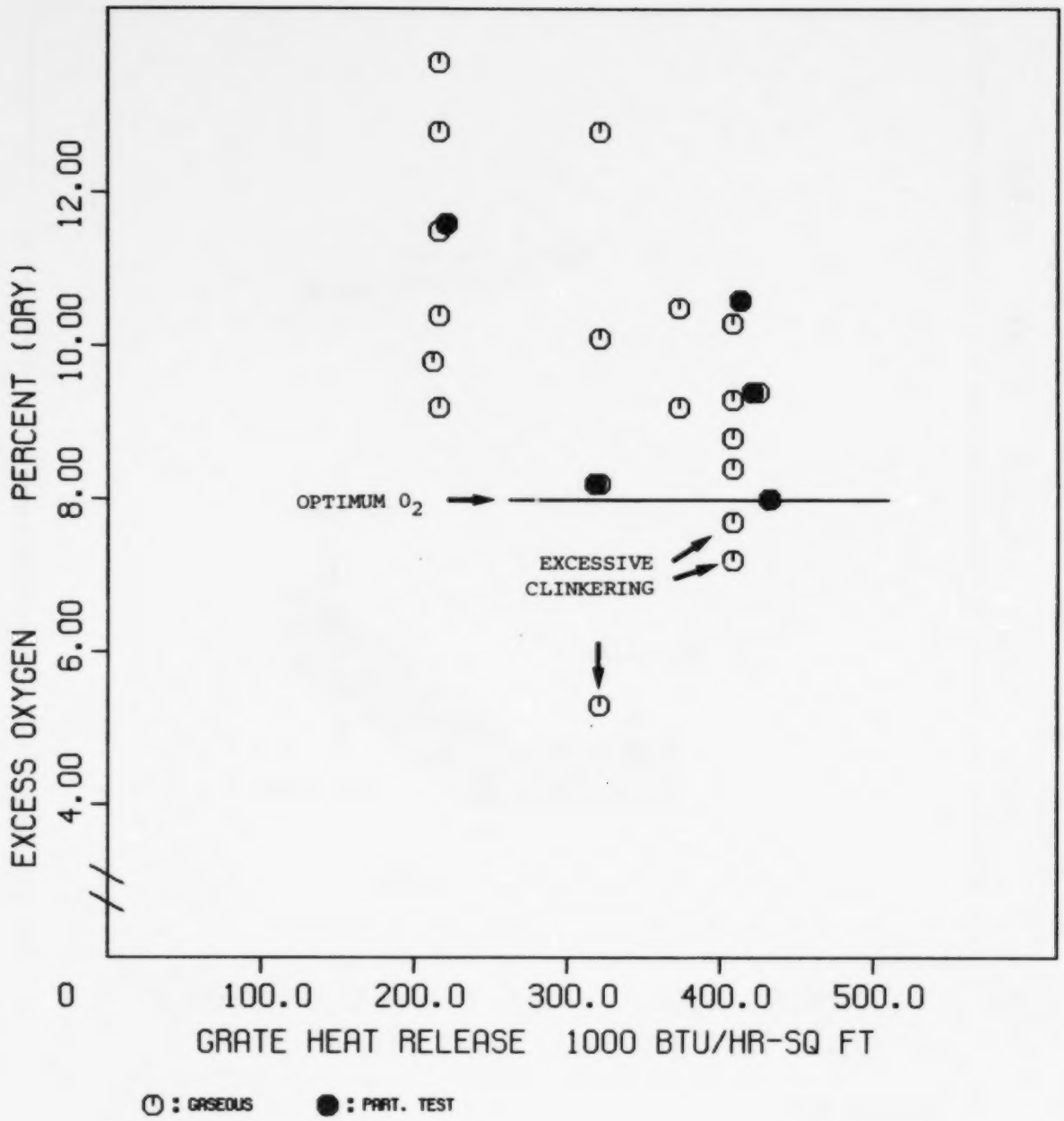

FIG. 5-2
EXCESS OXYGEN VS. GRATE HEAT RELEASE
TEST SITE H

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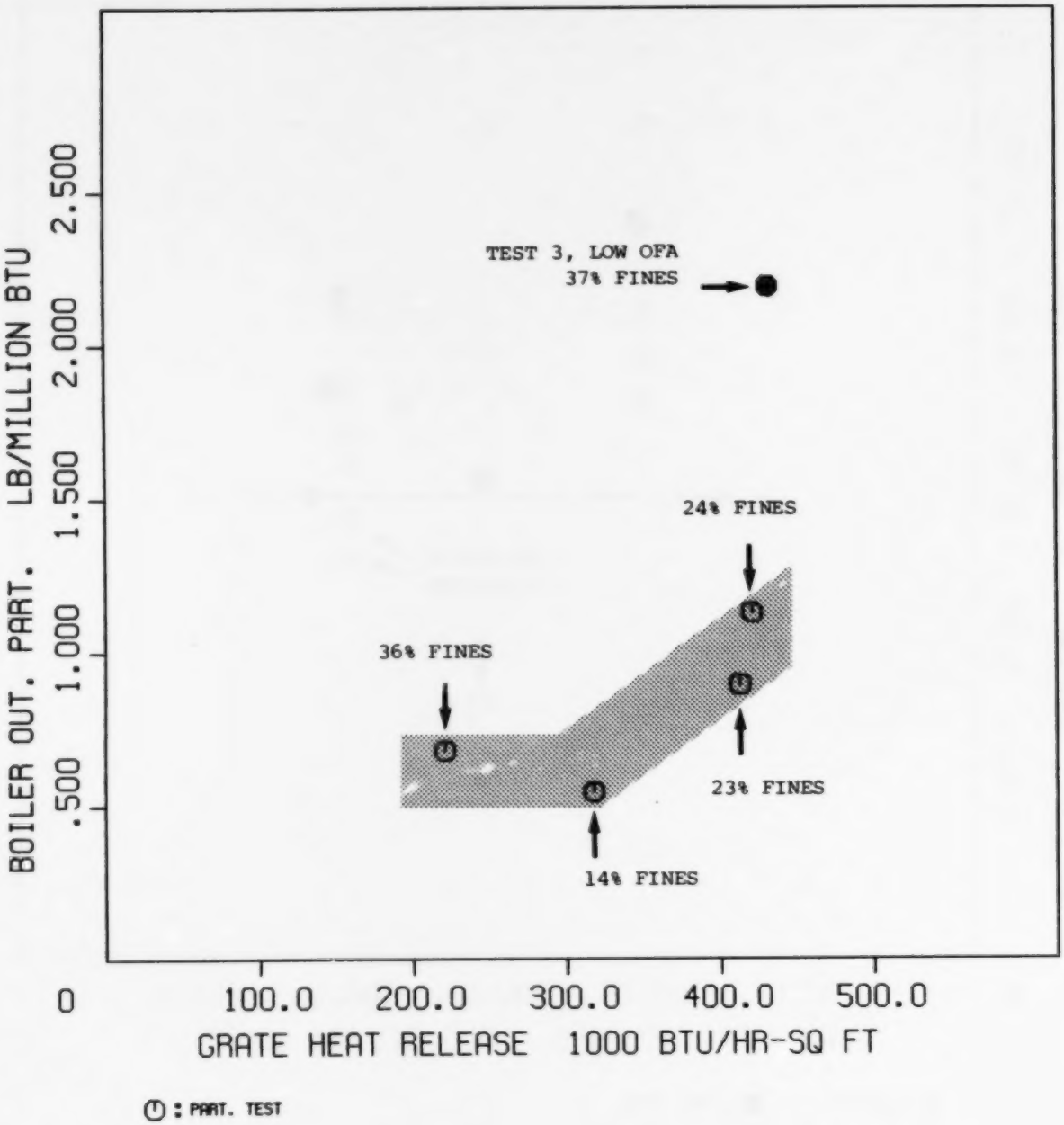

FIG. 5-3
BOILER OUT. PART. VS. GRATE HEAT RELEASE
TEST SITE H

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TABLE 5-7

ASH CARRYOVER VS LOAD
TEST SITE H

Test No.	% Capacity	Ash Content of Coal lb/10^6Btu	Ash Content of Flyash, lb/10^6Btu	Ash Carryover %
5	99	7.64	0.870	11.4
6	97	11.67	0.671	5.8
8	75	8.59	0.379	4.4
9	52	7.25	0.454	6.3

5.2.3 Nitric Oxide vs Oxygen and Grate Heat Release

Nitric oxide (NO) and nitrogen dioxide (NO_2) concentrations were measured during each test in units of parts per million (ppm) by volume. A chemiluminescent NOx analyzer was used to make these measurements. The ppm units have been converted to units of lb/10^6Btu in this report so they can be more easily compared with existing and proposed emission standards. Table 2-1 in the Executive Summary lists the nitric oxide data in units of ppm for the convenience of those who prefer these units.

Figure 5-4 presents the nitric oxide data as a function of grate heat release under the various excess air conditions encountered during testing. The average nitric oxide emissions increase as full boiler capacity is approached. Table 5-8 illustrates the trend of nitric oxide with load under normal operating conditions.

TABLE 5-8

NITRIC OXIDE VS LOAD AT NORMAL EXCESS AIR

	Oxygen % (dry)	Nitric Oxide lb/10^6Btu	Nitric Oxide ppm (dry) @ 3% O_2
100% Capacity	9.1±1.1	0.416±.059	307±44
75% Capacity	8.9±2.8	0.331±.108	244±80
50% Capacity	11.3±1.6	0.352±.023	260±17

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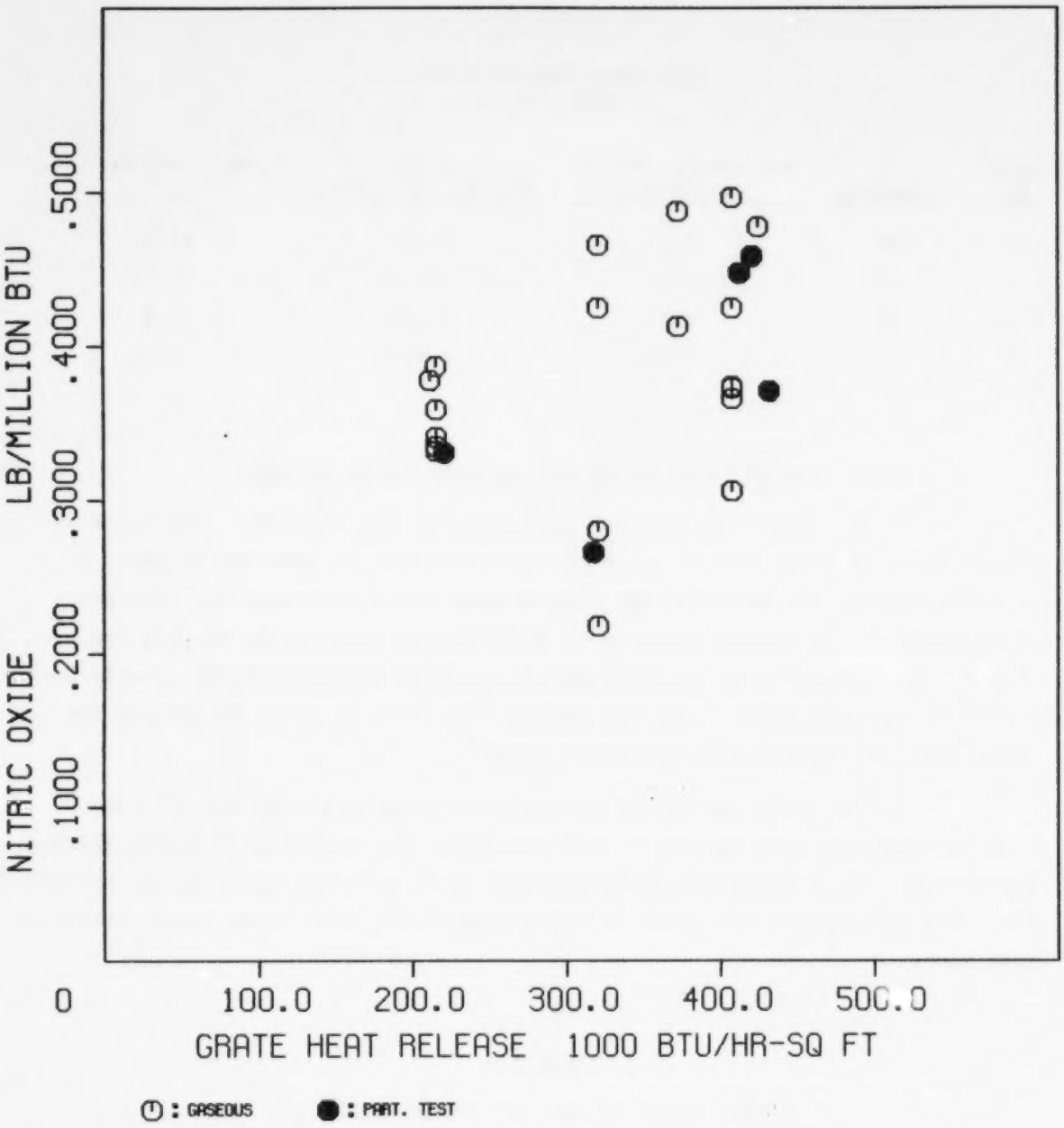

FIG. 5-4
NITRIC OXIDE VS. GRATE HEAT RELEASE
TEST SITE H

4-15900-542

When plotted as a function of oxygen, nitric oxide was found to relate to oxygen differently at the different loads. Figure 5-5 presents all of the nitric oxide data as a function of oxygen. Figures 5-6, 5-7, and 5-8 present the data for each of the three loads separately. In each plot, a trend line has been applied to the data by linear regression analysis. The slope of these trend lines indicate that nitric oxide increases by 0.055 lb NO/10^6Btu at full load, 0.041 lb NO/10^6Btu at 75% capacity and 0.006 lb NO/10^6Btu at 50% capacity. Thus, nitric oxide was found to be less sensitive to oxygen at lower loads.

Nitrogen dioxide (NO_2) was also measured at Site H. Of the twenty-one determinations made, eleven were zero and the remaining ten ranged from 0.001 to 0.018 lb/10^6Btu. The average was 0.004 lb/10^6Btu (3 ppm), or one percent of the total NOx. The NO_2 data is plotted as a function of grate heat release in Figure 5-9.

Concentrations of NO_2 this small are difficult to measure especially when NOx concentrations are varying with time. Such was the case at Site H. Therefore, averages are more meaningful than individual results. The reason for this is that with the chemiluminescent NOx analyzer NO_2 is determined as the difference between consecutive, not simultaneous, measurements of NOx and NO. Each of these measurements are accurate to about one percent at best. As an example, NO_2 = 384±4 ppm - 380±4 ppm = 4±8 ppm.

5.2.4 Sulfur Oxides vs Fuel Sulfur

Sulfur dioxide (SO_2) was measured during each test using an NDIR type continuous monitor. Sulfur trioxide (SO_3) was measured once using a wet chemical method called the Goksoyr-Ross method. The test data and their significance are discussed in this section.

Sulfur dioxide concentrations were directly related to the sulfur content of the fuel. SO_2 was not observed to vary with load or O_2. The small fraction of fuel sulfur which was not converted to SO_2 was either retained in the ash or converted to SO_3 and other sulfur compounds.

Sulfur dioxide is plotted as a function of fuel sulfur in Figure 5-10. The diagonal line in this plot represents 100% conversion of fuel sulfur to SO_2.

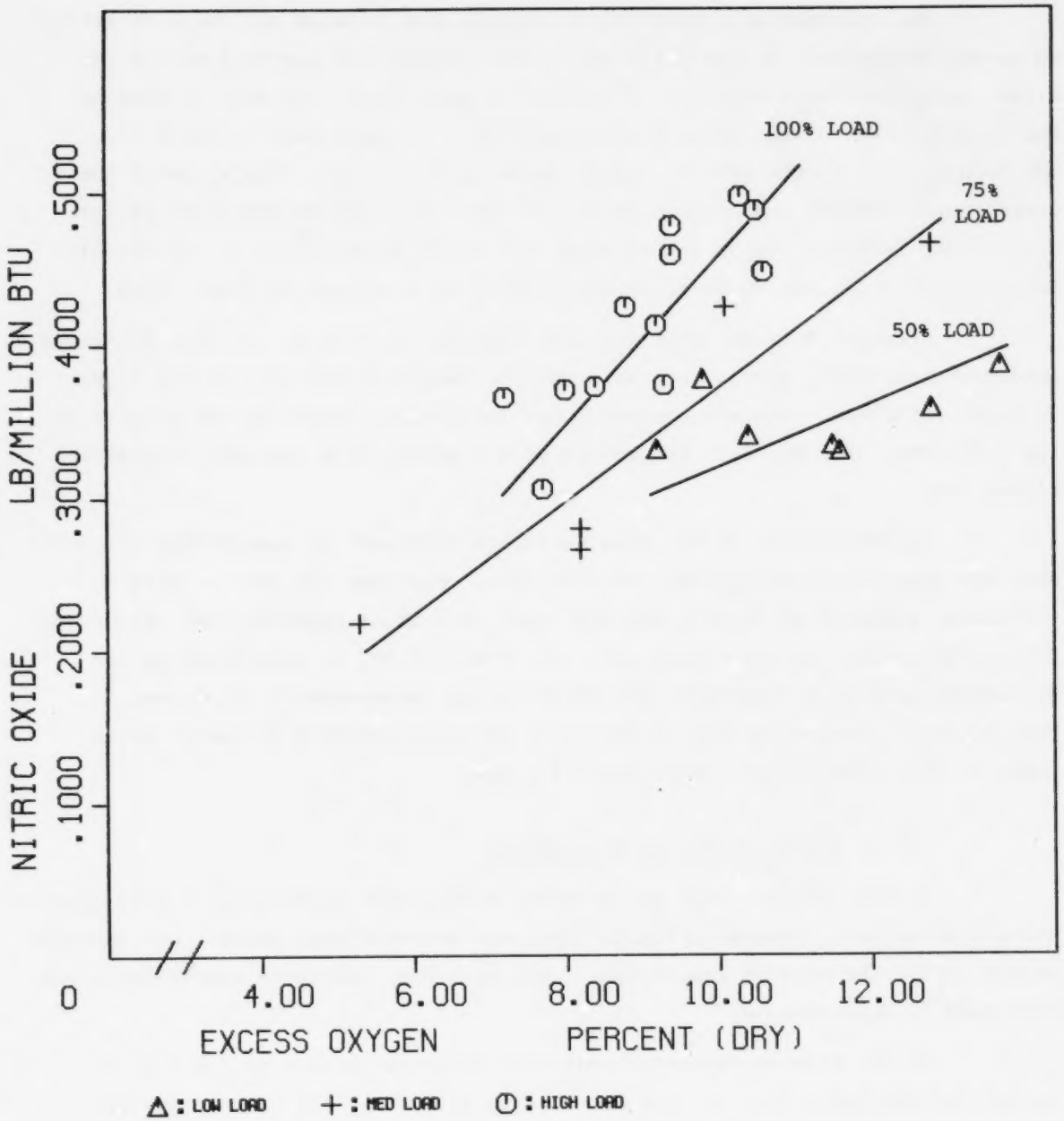

FIG. 5-5
NITRIC OXIDE VS. EXCESS OXYGEN
TEST SITE H

SOLID LINES REPRESENT TRENDS AT THREE LOADS AS DETERMINED BY LINEAR REGRESSION ANALYSIS

4-15900-542

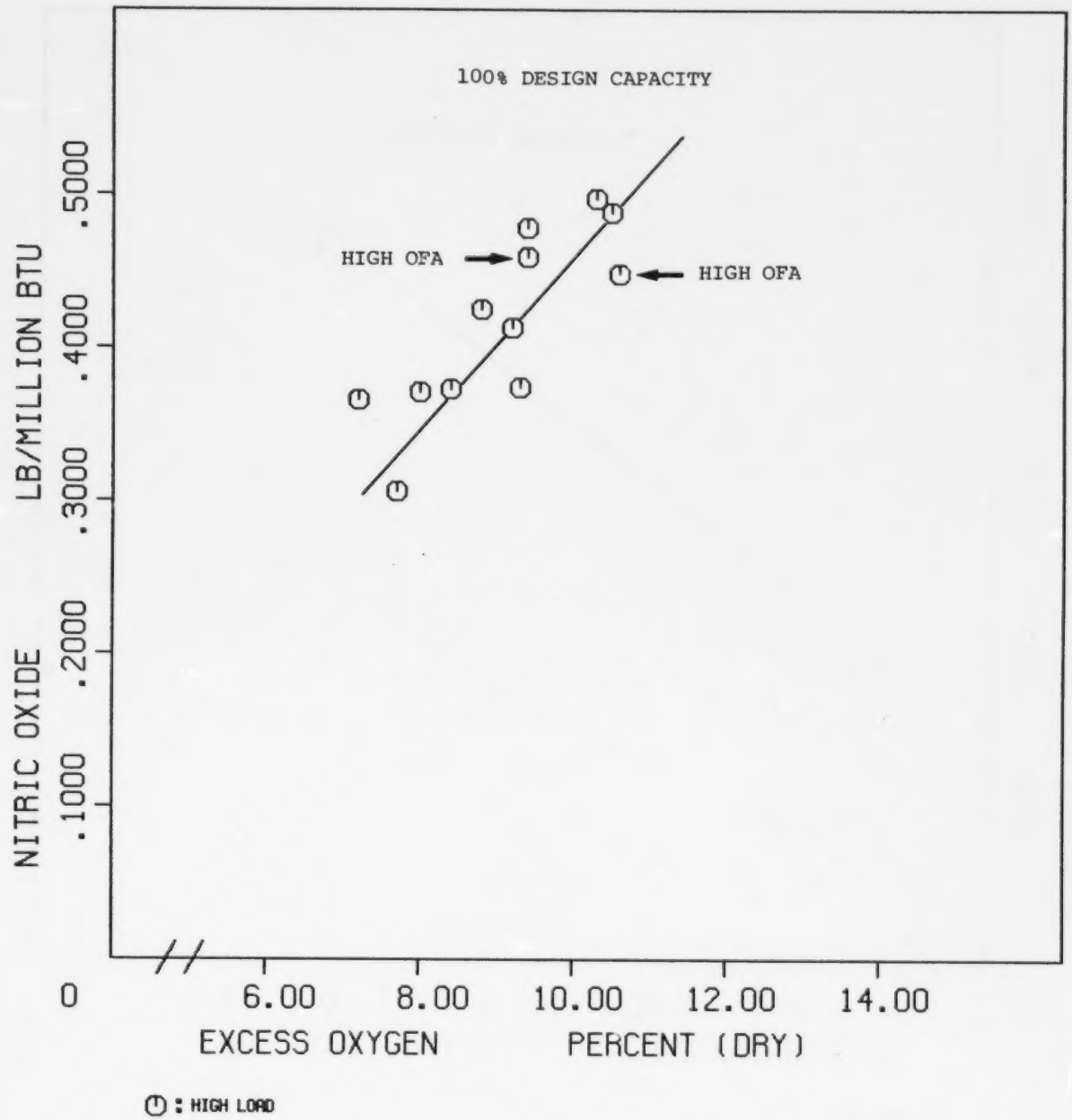

FIG. 5-6
NITRIC OXIDE VS. EXCESS OXYGEN
TEST SITE H

TREND LINE DETERMINED BY LINEAR REGRESSION ANALYSIS, SLOPE = 0.055, COEFFICIENT OF DETERMINATION (R) = 0.83, HIGH OVERFIRE AIR IS SHOWN TO HAVE NO EFFECT ON NITRIC OXIDE CONCENTRATION.

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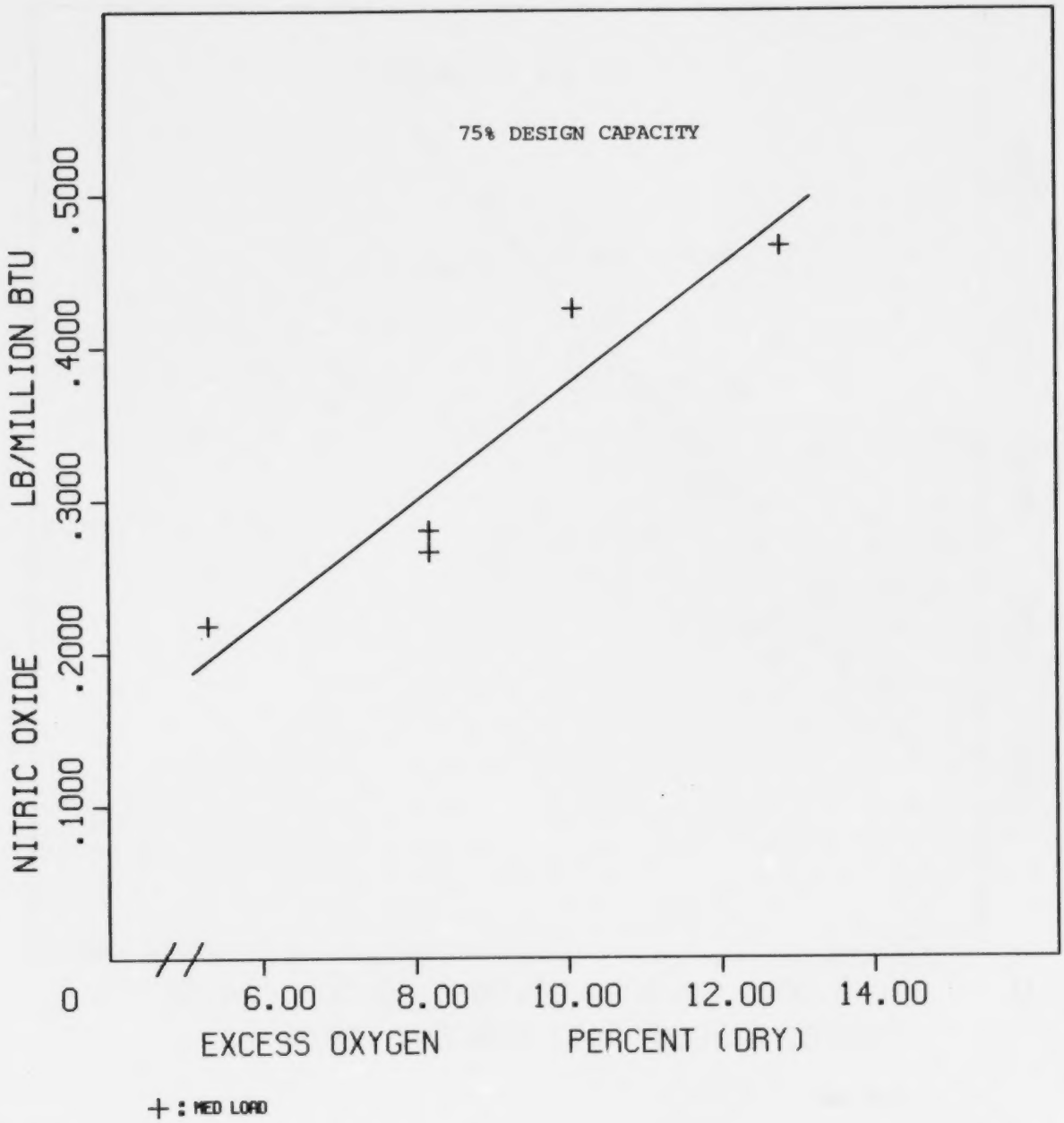

FIG. 5-7
NITRIC OXIDE VS. EXCESS OXYGEN
TEST SITE H

TREND LINE DETERMINED BY LINEAR REGRESSION ANALYSIS,
SLOPE + 0.040, COEFFICIENT OF DETERMINATION (R) = 0.94.

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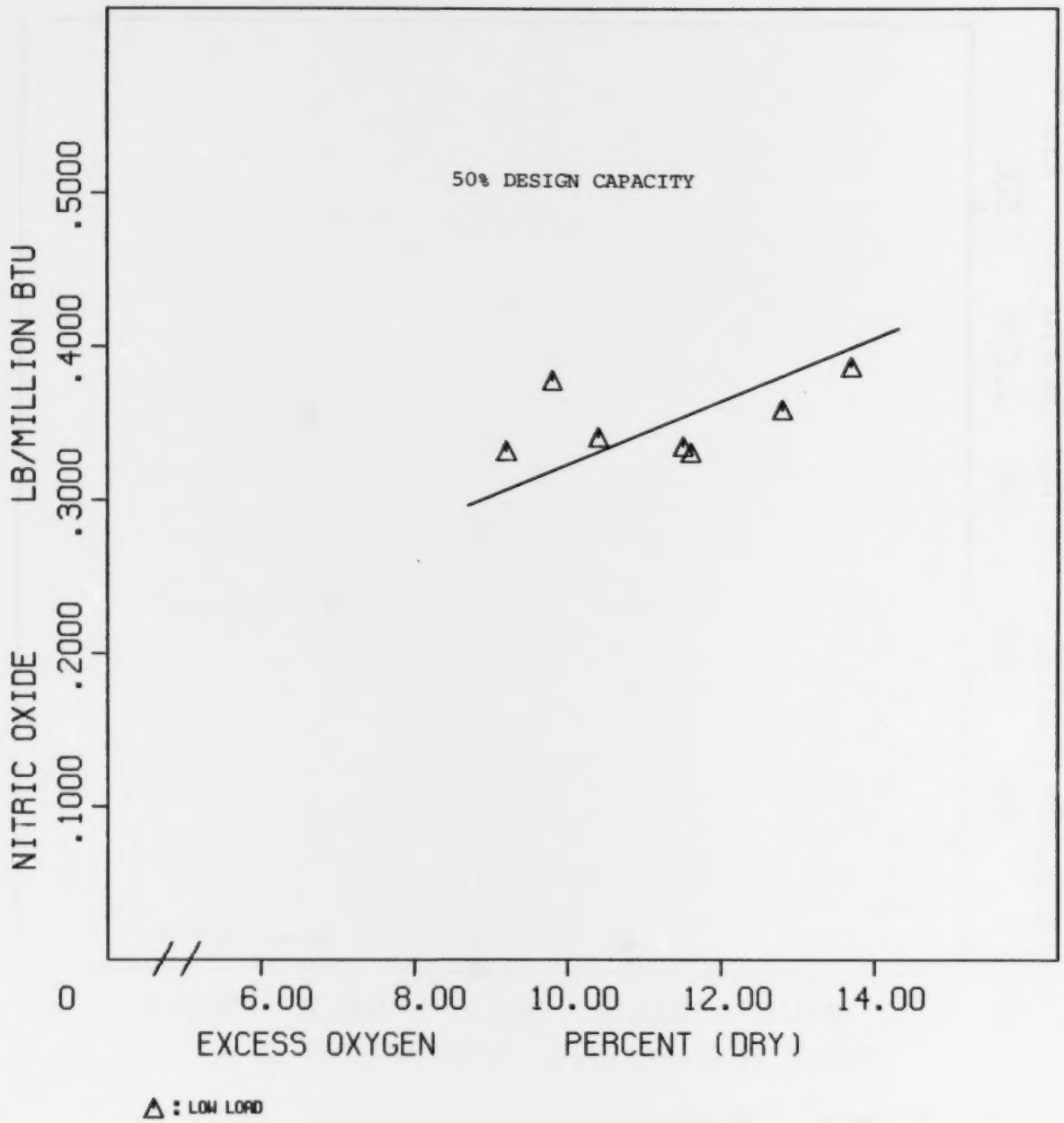

FIG. 5-8
NITRIC OXIDE VS. EXCESS OXYGEN
TEST SITE H

TREND LINE DETERMINED BY LINEAR REGRESSION ANALYSIS,
SLOPE = 0.019, COEFFICIENT OF DETERMINATION (R) = 0.44

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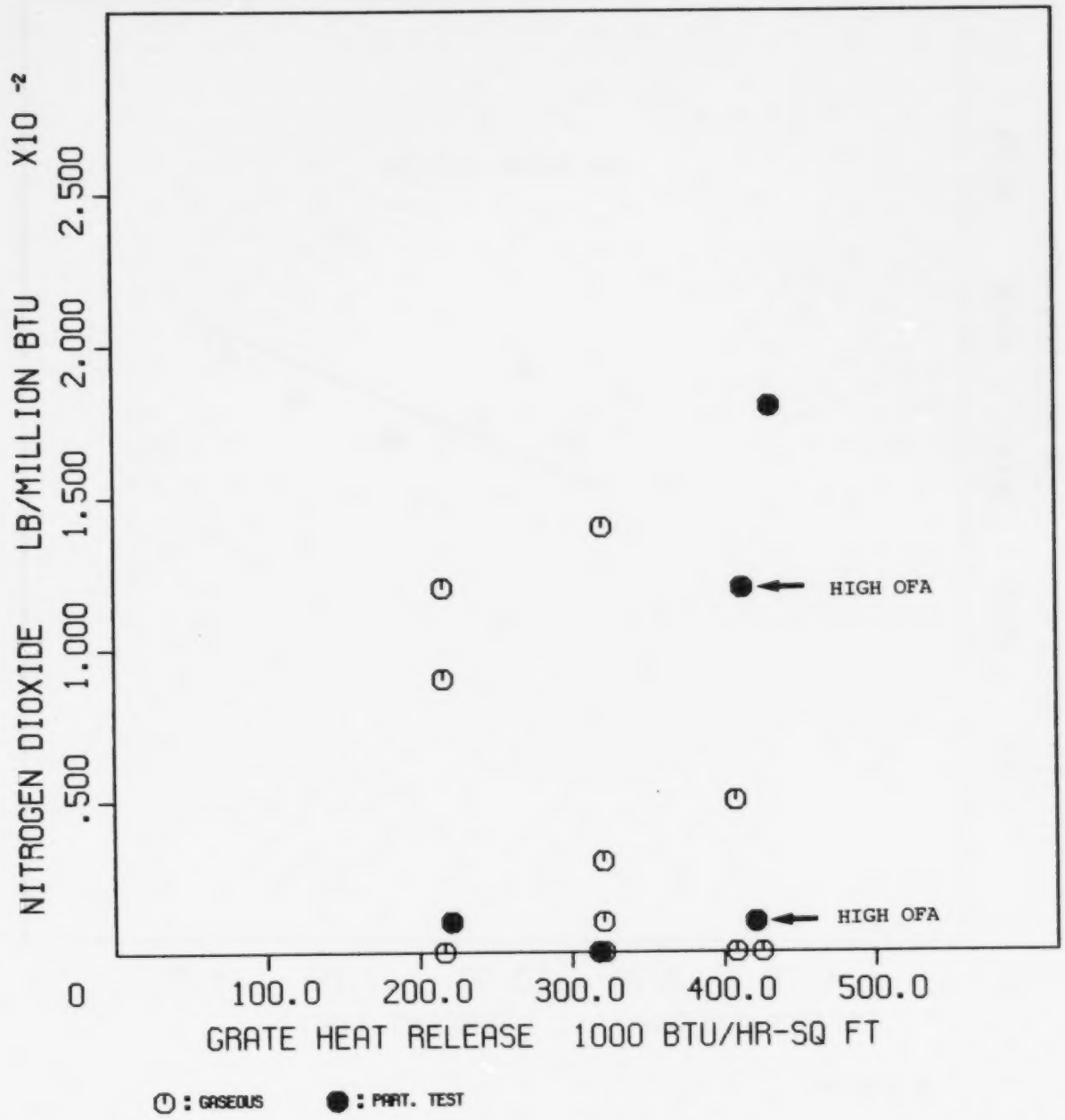

FIG. 5-9
NITROGEN DIOXIDE VS. GRATE HEAT RELEASE
TEST SITE H

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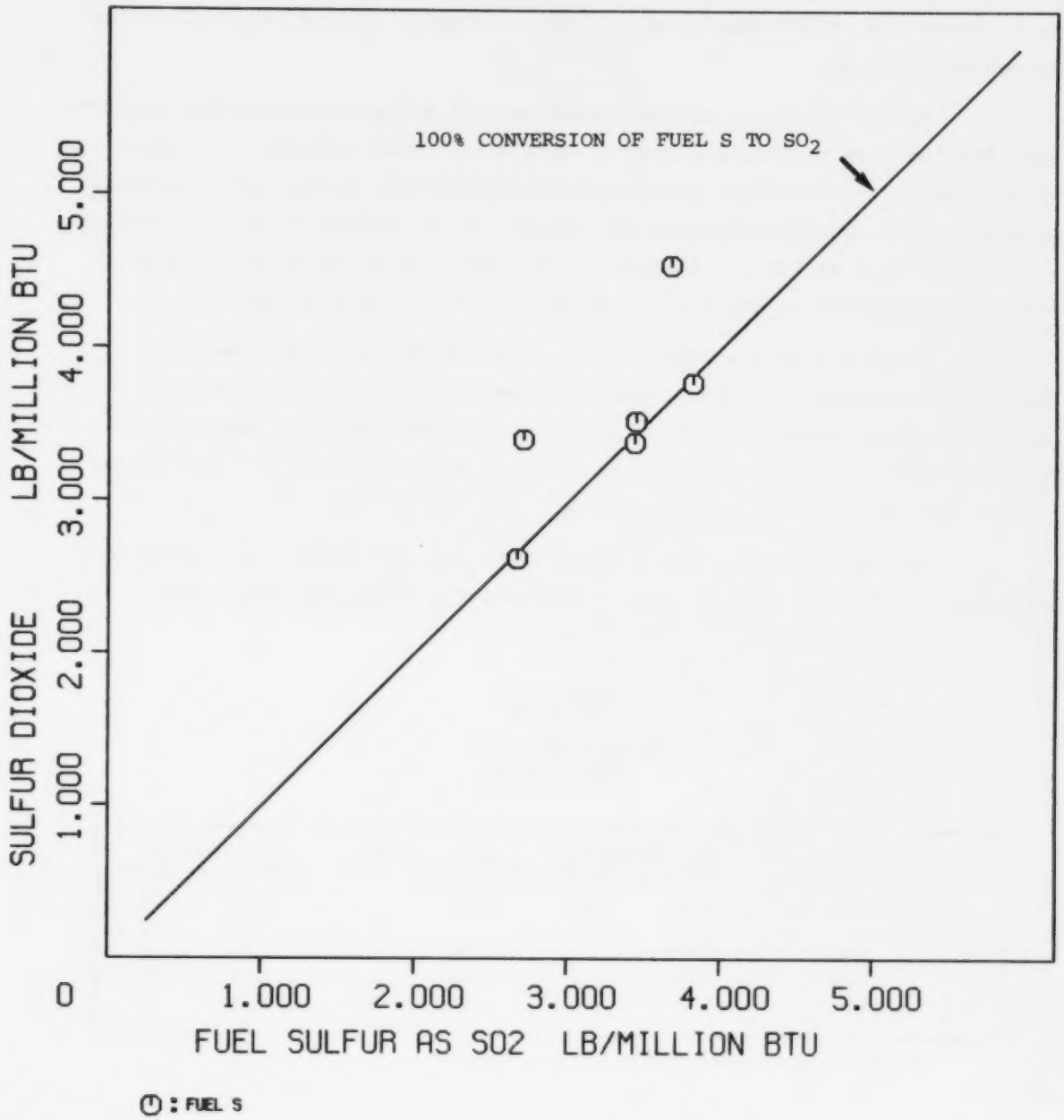

FIG. 5-10
SULFUR DIOXIDE VS. FUEL SULFUR AS SO2
TEST SITE H

4-15900-542

It is shown that within measurement error, virtually 100% of the fuel sulfur is converted to SO_2.

Sulfur retention in the bottom ash was determined by direct measurement for the five particulate tests. This data, shown in Table 5-9, shows that an average 2.9% of the fuel sulfur was retained in the bottom ash. Assuming similar sulfur concentrations in the flyash, it is calculated that an average 0.4% of the fuel sulfur is retained in this ash. Thus, 96.7% of the fuel sulfur is converted to SO_2 and SO_3 while 3.3% is retained in the ash.

Table 5-9 is a sulfur balance on Boiler H. With the exception of Test 8, the balance is within acceptable limits for measurement accuracy. Even the six percent average of Test 5 could be accounted for by a fuel sulfur determination error of only 0.13% (i.e. 2.10% sulfur instead of 1.97% sulfur in the fuel would yield 100% balance).

Sulfur trioxide (SO_3) was measured once during Test 11 and found to be 0.065 lb/10^6Btu (33 ppm). This is 1.9% of the total SOx (SO_2 + SO_3).

TABLE 5-9

SULFUR BALANCE
TEST SITE H

Test No.	Sulfur in Fuel lb/10^6Btu as SO_2(A)	Sulfur in Bottom Ash lb/10^6Btu as SO_2	% of (A)	Sulfur in Flyash* lb/10^6Btu as SO_2	% of (A)	Sulfur in Flue Gas lb/10^6Btu as SO_2	% of (A)
3	2.667	0.064	2.4	0.026	1.0	2.617	98.1
5	3.449	0.128	3.7	0.017	0.5	3.524	102.2
6	3.441	0.077	2.2	0.005	0.2	3.378	98.2
8	3.678	0.155	4.2	0.008	0.2	4.539	123.4
9	3.822	0.083	2.2	0.007	0.2	3.770	98.6

* % Sulfur in Flyash Assumed to be the Same as in Bottom Ash

5.2.5 Hydrocarbons vs Oxygen and Grate Heat Release

Unburned hydrocarbons (HC) were measured with a heated sample line and a continuous monitoring instrument utilizing the flame ionization method of detection. Test data are plotted as a function of grate heat release in Figure 5-11, and as a function of oxygen in Figure 5-12.

There is some indication that the concentration of hydrocarbons in the flue gas increased as the load decreased. This slight dependence on load is illustrated in Table 5-10.

TABLE 5-10

HYDROCARBONS VS BOILER LOAD
TEST SITE H

	No. of Measurements	Average HC, ppm
100% Capacity	3	51±55
75% Capacity	5	78±39
50% Capacity	6	104±24

Hydrocarbon concentrations were found to be highly dependent on oxygen as shown in Figure 5-12. Hydrocarbon concentration increased as oxygen increased. Figure 5-12 also illustrates how high overfire air effectively reduced the hydrocarbon concentration at high load.

5.2.6 Carbon Monoxide vs Oxygen and Grate Heat Release

Carbon monoxide (CO) was measured with an NDIR continuous monitor in units of parts per million (ppm) by volume. The data are plotted as a function of grate heat release in Figure 5-13, and as a function of oxygen in Figure 5-14.

Carbon monoxide concentrations were found to increase slightly with load, and to be at their minimum at 9% O_2. In general, carbon monoxide concentrations remained well below 400 ppm (0.04%), which is considered acceptable for a coal-fired stoker boiler. Unacceptable conditions included excess oxygen below 6% or above 13%, and low overfire air at high loads.

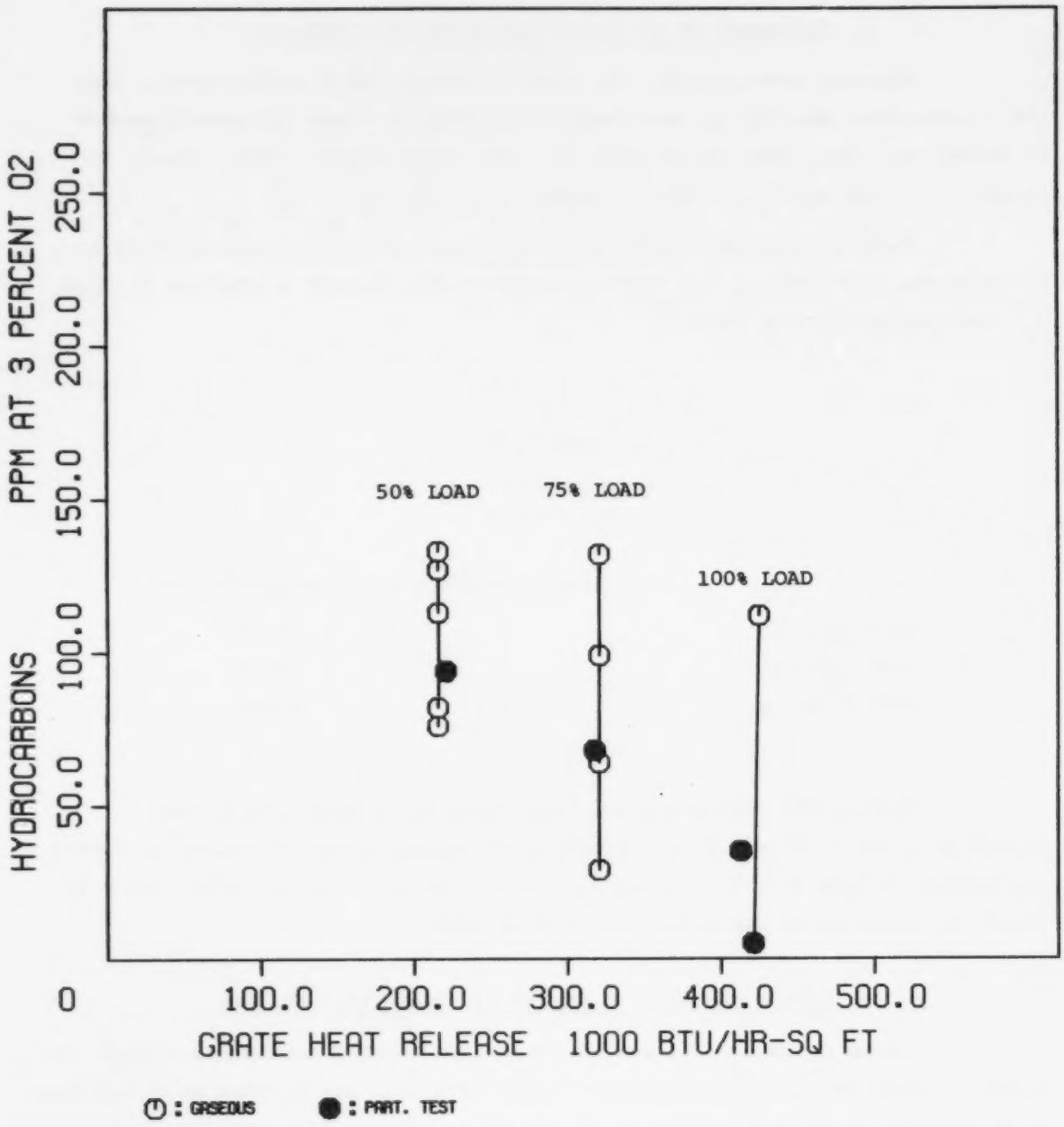

FIG. 5-11
HYDROCARBONS VS. GRATE HEAT RELEASE
TEST SITE H

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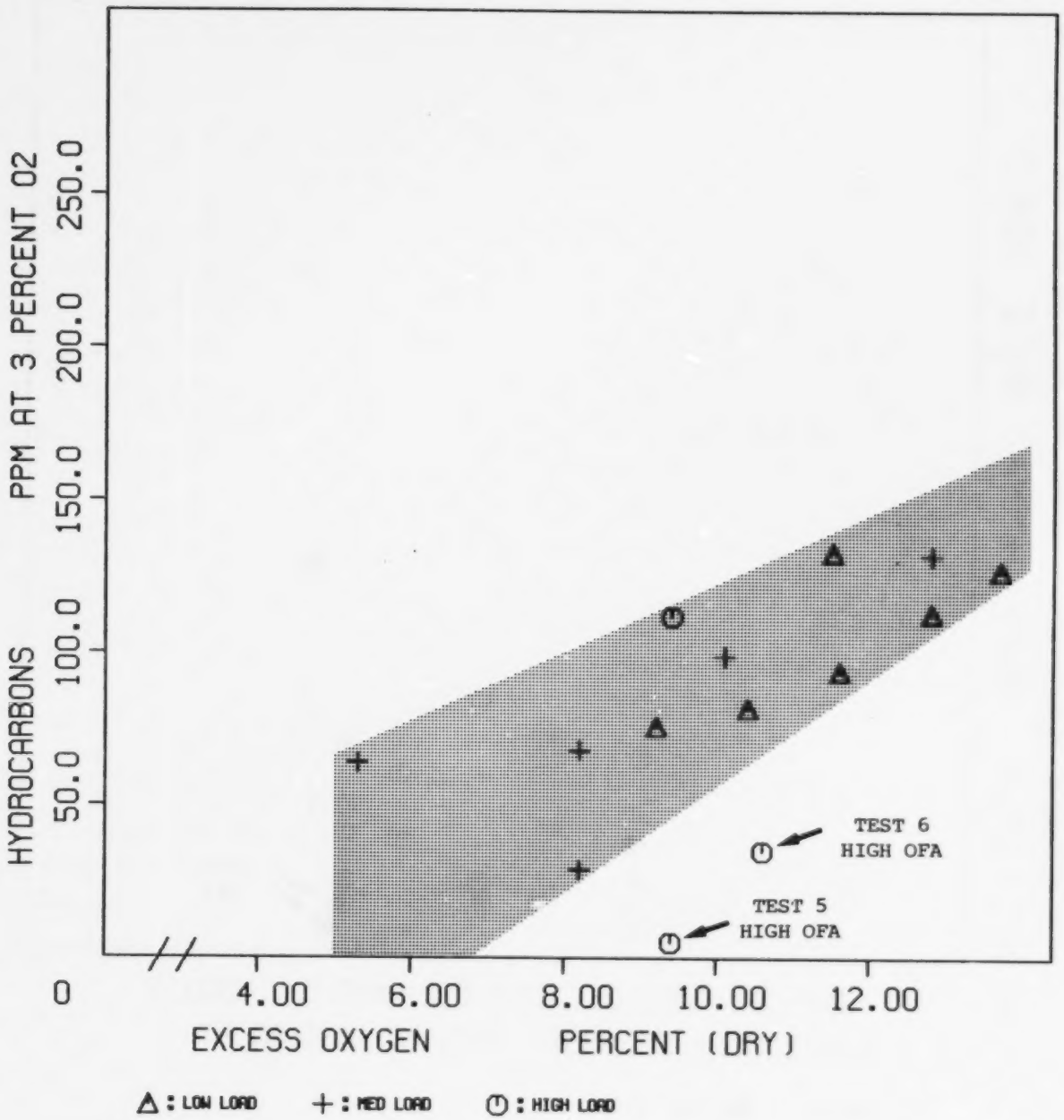

FIG. 5-12
HYDROCARBONS VS. EXCESS OXYGEN
TEST SITE H

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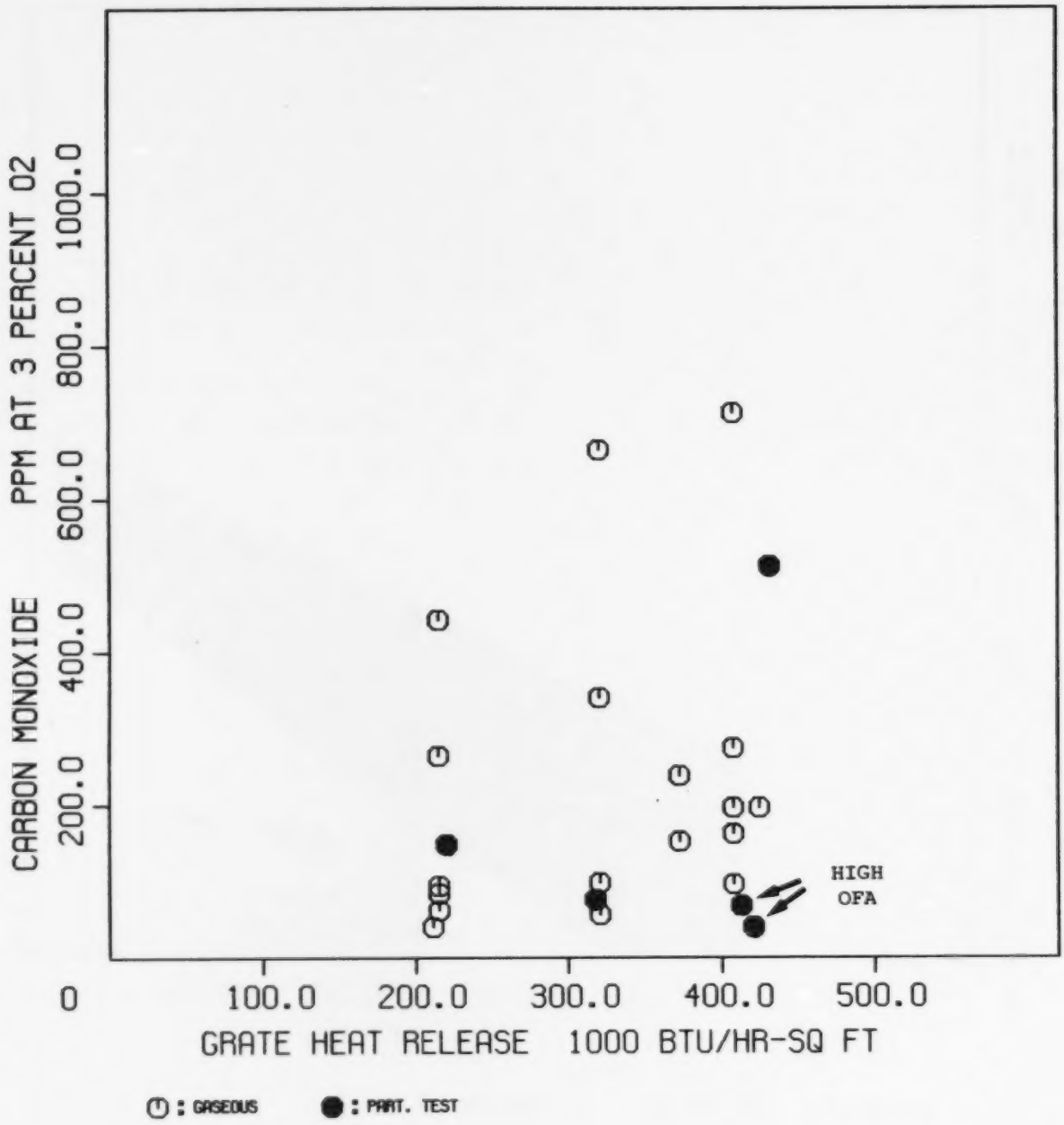

FIG. 5-13
CARBON MONOXIDE VS. GRATE HEAT RELEASE
TEST SITE H

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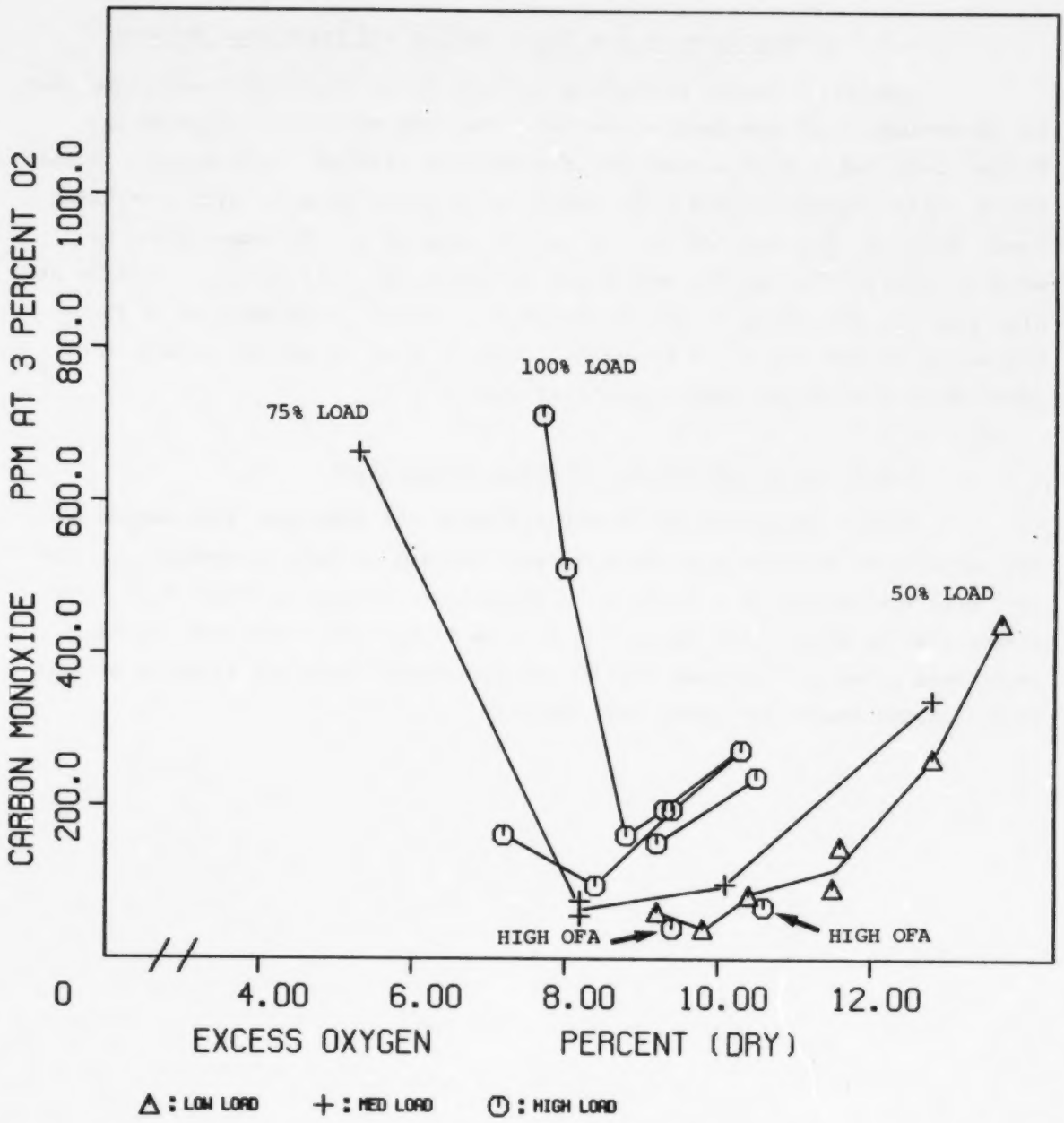

FIG. 5-14

CARBON MONOXIDE VS. EXCESS OXYGEN
TEST SITE H

SOLID LINES REPRESENT OBSERVED TRENDS AT THE THREE LOADS

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5.2.7 Combustibles in the Ash vs Oxygen and Grate Heat Release

Samples of flyash and bottom ash were baked in a high temperature oven for determination of combustible content. The test results are plotted in Figures 5-15 and 5-16 as a function of grate heat release. Combustibles in the boiler outlet flyash (Figure 5-15) appear to decrease slightly with increasing load. However, they all fall in the narrow range of 23-33% combustibles by weight. Combustibles in the bottom ash (Figure 5-16) also decrease slightly at high load but not enough to be considered significant. Combustibles in the bottom ash ranged from 7-21% by weight. Combustibles in the ash showed no correlation with excess oxygen in either case.

5.2.8 Boiler Efficiency vs Grate Heat Release

Boiler efficiency was determined using the ASME heat loss method for all tests which included a particulate mass loading or SASS determination. The test data are plotted as a function of grate heat release in Figure 5-17. The shaded area on this figure represents how the boiler efficiency may relate to grate heat release. It shows that boiler efficiency drops off slightly at full load (425,000 Btu/hr-ft^2 grate heat release).

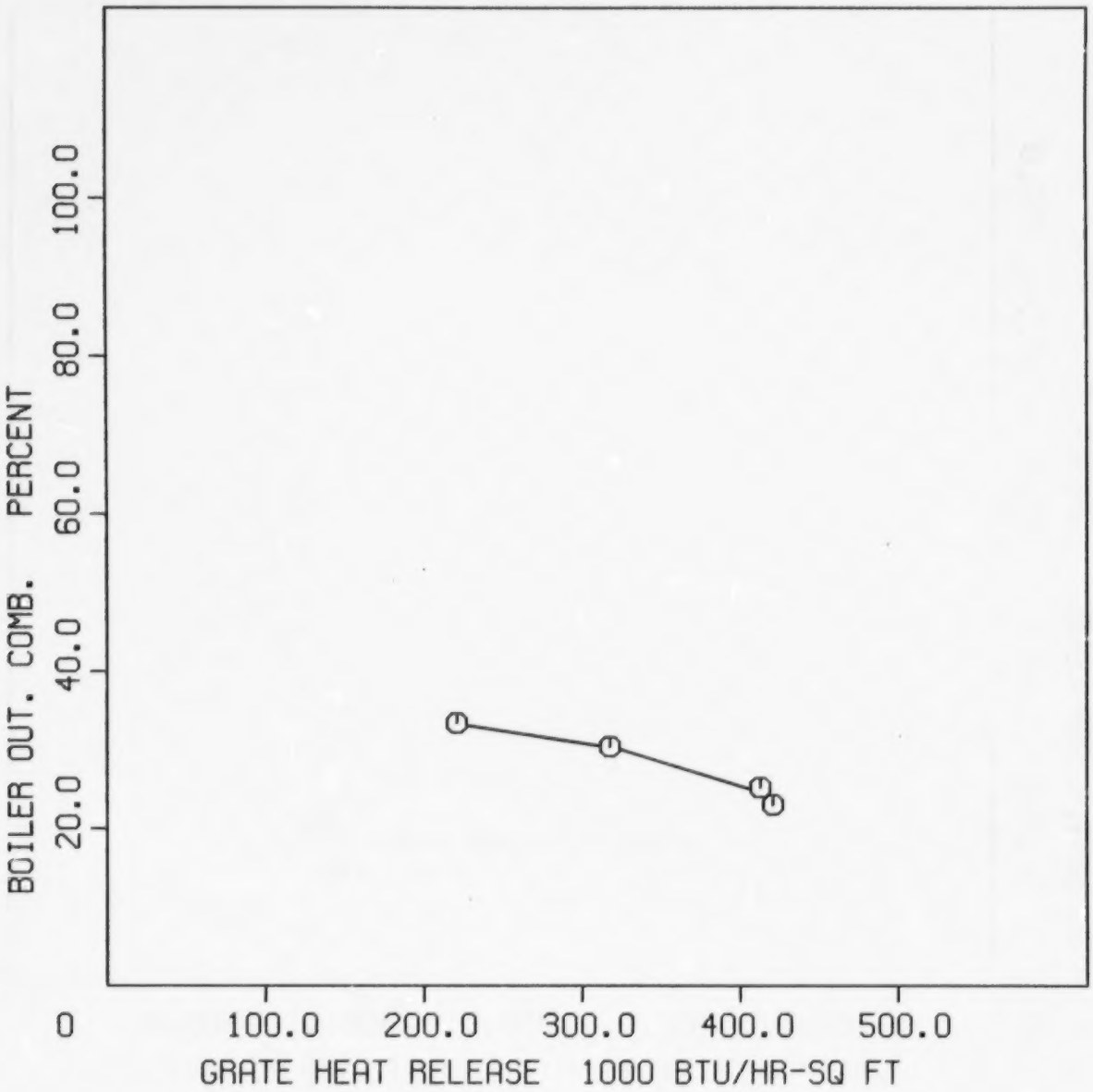

FIG. 5-15
BOILER OUT. COMB. VS. GRATE HEAT RELEASE
TEST SITE H

4-15900-542

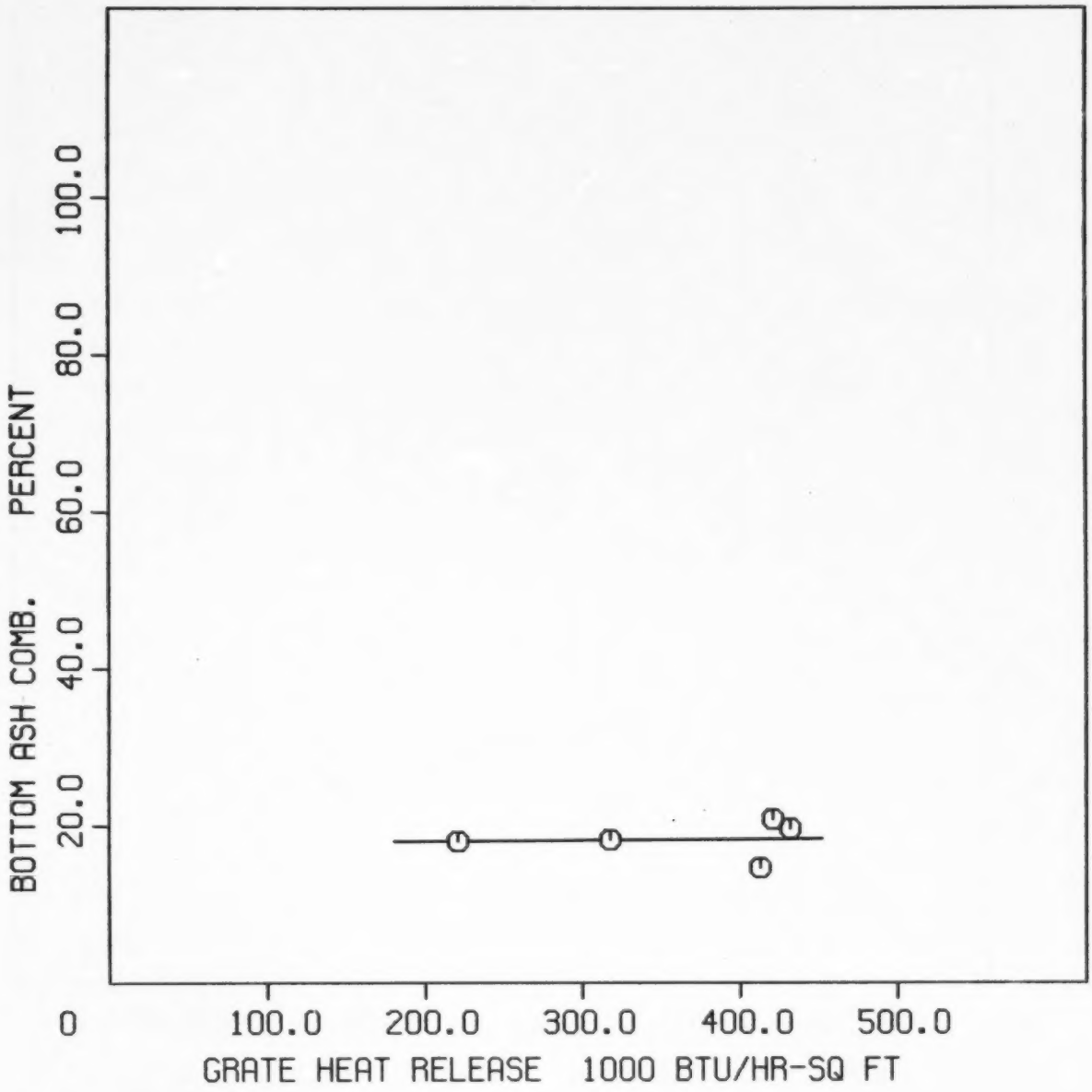

FIG. 5-16
BOTTOM ASH COMB. VS. GRATE HEAT RELEASE
TEST SITE H

4-15900-542

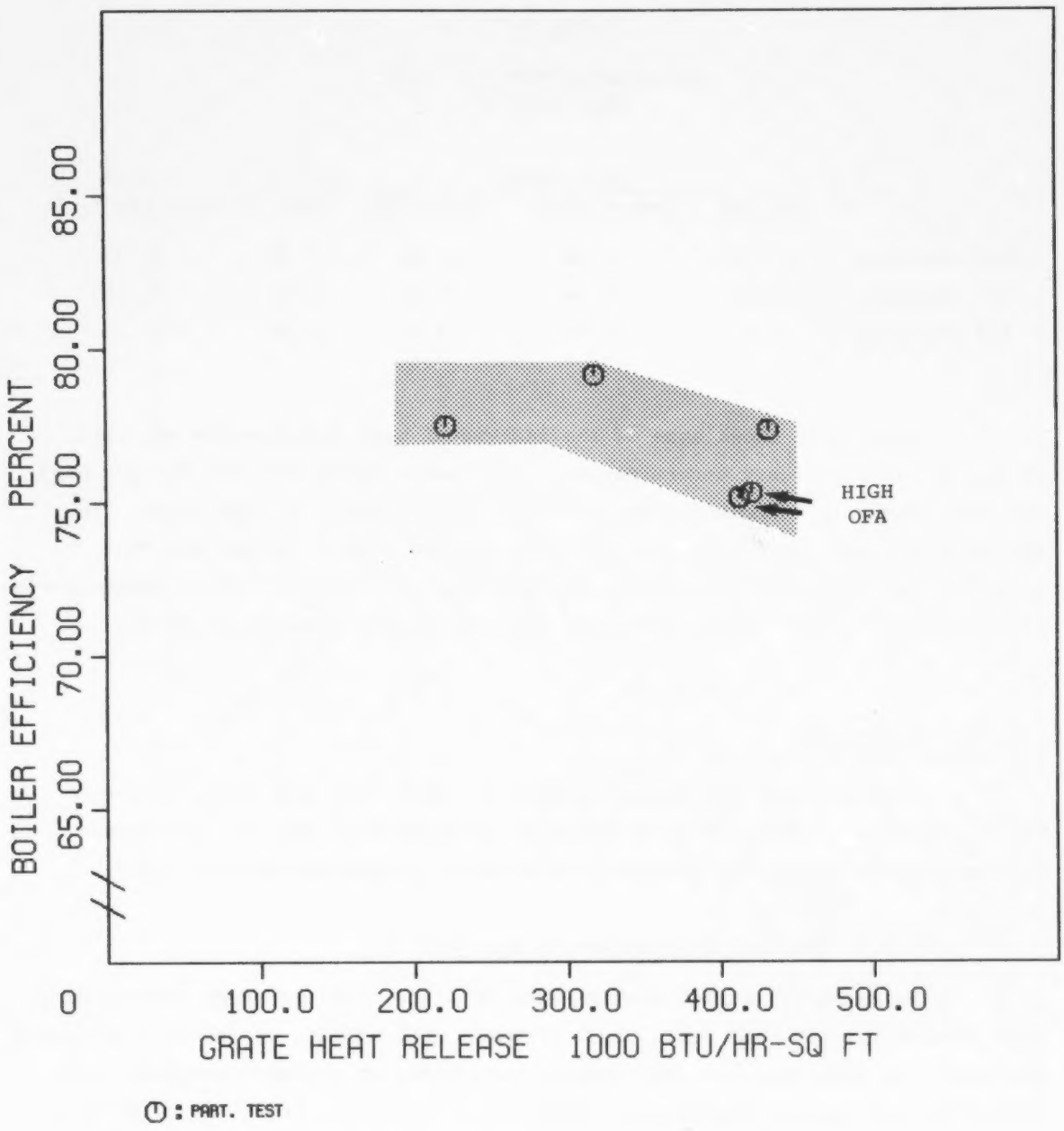

FIG. 5-17
BOILER EFFICIENCY VS. GRATE HEAT RELEASE
TEST SITE H

4-15900-542

TABLE 5-11

BOILER EFFICIENCY VS LOAD
TEST SITE H

	HEAT LOSSES, %				BOILER EFFICIENCY, %
	Dry Gas	Combustibles	Radiation	Other	
100% Capacity	14.52	2.32	0.65	7.12	75.39
75% Capacity	10.23	2.84	0.86	6.92	79.15
50% Capacity	12.13	2.46	1.23	6.66	77.52

Table 5-11 shows some of the individual heat losses which are part of the boiler efficiency determination. This table shows that the dry gas heat loss was primarily responsible for the drop in efficiency at high loads. The dry gas heat loss represents the heat lost out the stack. At 50% and 75% capacity, the stack gas temperature was measured at 335°F and 381°F, respectively. At 100% capacity the average stack gas temperature was measured at 477°F.

5.3 COAL PROPERTIES

Only one coal was tested at Site H. This coal came from the Sands Hill strip mine in Ohio and is referred to as Sands Hill coal in this report. This section describes the chemical and physical properties of this coal.

5.3.1 Chemical Composition of the Coal

Representative coal samples were obtained from the weigh lorry during each particulate and SASS test. Each of these coal samples was given a proximate analysis. In addition, two coal samples were given an ultimate analysis, and tested for ash fusion temperature, Hardgrove grindability index, free swelling index, and mineral composition of the ash. The data from these analyses are presented in Tables 5-12 and 5-13.

TABLE 5-12

FUEL ANALYSIS - SANDS HILL COAL
TEST SITE H

TEST NO.	3	5	6	8	9	11	AVG	STD DEV
PROXIMATE (As Rec'd)								
% Moisture	10.76	13.01	12.31	11.19	10.90	11.20	11.56	0.90
% Ash	7.10	8.73	12.34	9.62	8.38	5.52	8.62	2.32
% Volatile	35.88	33.53	33.43	36.21	34.42	37.51	35.16	1.63
% Fixed Carbon	46.26	44.73	41.92	42.98	46.30	45.77	44.66	1.83
Btu/lb	11773	11421	10577	11201	11566	11963	11417	447
% Sulfur	1.57	1.97	1.82	2.06	2.21	1.62	1.88	0.25
ULTIMATE (As Rec'd)								
% Moisture			12.31			11.20	11.76	0.78
% Carbon			59.29			67.17	63.73	5.57
% Hydrogen			4.15			4.56	4.36	0.29
% Nitrogen			1.04			1.11	1.08	0.05
% Chlorine			0.09			0.05	0.07	0.03
% Sulfur			1.82			1.62	1.72	0.14
% Ash			12.34			5.52	8.93	4.82
% Oxygen			8.96			8.77	8.87	0.13
ASH FUSION (Red)								
Initial Deformation			2400°F			2010°F	2205	276
Softening (H=W)			2550°F			2175°F	2363	265
Softening (H=1/2W)			2590°F			2215°F	2403	265
Fluid			2700+°F			2495°F	2598	145
HARDGROVE GRINDABILITY INDEX			43			49	46	4.24
FREE SWELLING INDEX			1-1/2			2	1.75	0.35

TABLE 5-13

MINERAL ANALYSIS OF COAL ASH
(SANDS HILL COAL)
TEST SITE H

TEST NO.		6	11	AVG
MINERAL ANALYSIS OF ASH				
Silica	SiO_2	47.93	39.73	43.83
Alumina	Al_2O_3	27.35	23.32	25.34
Titanic	TiO_2	1.06	1.12	1.09
Ferric Oxide	FeO_3	16.19	28.23	22.21
Lime	CaO	1.59	1.91	1.75
Magnesia	MgO	0.72	0.62	0.67
Potassium Oxide	K_2O	2.03	1.74	1.89
Sodium Oxide	Na_2O	0.29	0.23	0.26
Phos. Pentoxide	P_2O_5	0.33	0.36	0.35
Sulfur Trioxide	SO_3	0.78	0.66	0.72
Undetermined		1.61	1.99	1.80
Silica Value		72.15	56.36	64.26
Base: Acid Ratio		0.27	0.51	0.39
T_{250} Temperature		2595°F	2300°F	2448
SULFUR FORMS				
% Pyritic		0.86	0.96	0.91
% Organic		0.73	0.66	0.79
% Sulfate		0.23	0.00	0.12

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5.3.2 Coal Size Consistency

The individual coal samples were screened at the site using 1", 1/2", 1/4", #8 and #16 square mesh screens. The results of these screenings are presented in Table 5-14. The standard deviation of the coal size consistency is plotted against the ABMA recommended limits for overfeed stokers in Figure 5-18. This figure shows the as-fired coal to be on the low-fines side of the recommended range. This is a good coal size. Coal fines, defined as the percent by weight passing a 1/4" screen, averaged 25.9%.

TABLE 5-14

AS FIRED COAL SIZE CONSISTENCY
SANDS HILL COAL
TEST SITE H

Test No.	PERCENT PASSING STATED SCREEN SIZE				
	1"	1/2"	1/4"	#8	#16
3	95.9	63.3	36.6	18.5	13.3
5	94.8	60.9	23.5	9.8	6.4
6	92.7	59.4	23.2	9.4	6.2
8	88.5	44.0	14.4	5.2	3.2
9	95.1	67.1	35.8	16.4	11.1
11	91.5	48.5	22.0	9.7	6.8
Average	93.1	57.2	25.9	11.5	7.8

As one might expect, coal fines appear to play a role in particulate mass loading. In Figure 5-3, page 42, coal fines are indicated for each particulate data point. The increase in particulate loading between the intermediate load and low load tests is very likely due to the differences in coal fines between the two tests. Also, the fact that the low overfire air test was conducted during a period of high coal fines very likely contributed to the resultant high particulate mass loading.

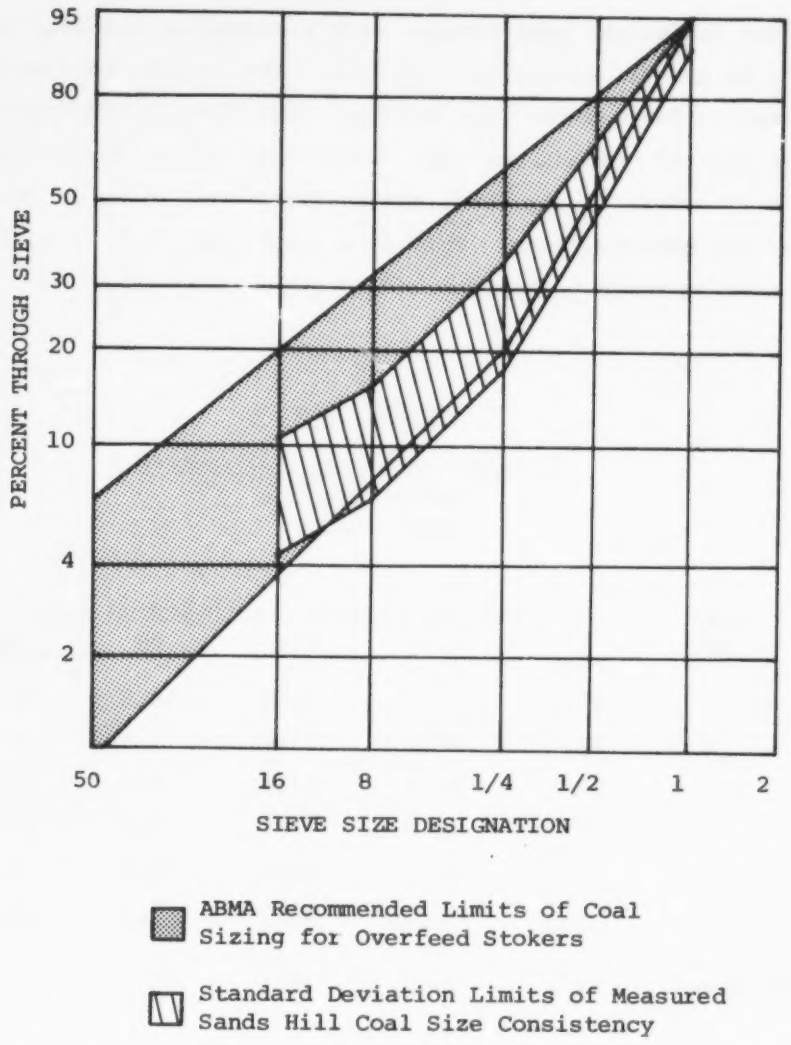

Figure 5-18. Size Consistency of "As Fired" Sands Hill Coal vs ABMA Recommended Limits of Coal Sizing for Overfeed Stokers - Test Site H.

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5.4 PARTICLE SIZE DISTRIBUTION OF FLYASH

Three particle size distribution determinations were made of the uncontrolled particulate matter in the flue gas. These determinations were made using a Bahco classifier and sieve, a Brink cascade impactor, and a SASS cyclone train. Firing conditions for the three tests are shown in Table 5-15.

TABLE 5-15

DESCRIPTION OF PARTICLE SIZE DISTRIBUTION TESTS
TEST SITE H

Test No.	Boiler Capacity %	O_2 %	OFA	Particle Size Distribution Methodology Used
3	102	8.0	Low	Bahco Classifier - Sieve
5	99	9.4	High	Brink Cascade Impactor
11	100	9.2	Low	SASS Cyclones

The test results are presented in Table 5-16 and in Figures 5-19, 5-20 and 5-21. The test results are as different as the sample methodologies. A discussion of each method is included in Section 4.4 and may be worth reviewing.

The Bahco classifier sample was collected with a cyclone followed by a backup filter. As a result, a fraction of the sample (12.2%) was not captured by the cyclone and was not part of the sample processed by the Bahco classifier. Thus, the results of this test are biased such that they indicate fewer particles below about 15 micrometers than there actually were. It is hoped that appropriate corrections can be made to the Bahco data at some future date using the measured cyclone collection efficiency (87.8%) and the theoretical cyclone collection efficiencies by particle size.

The Brink and SASS particle size distribution data should be accurate and require no corrections. However, these are single point measurements, whereas the Bahco data was obtained with a 24-point traverse of the duct. Single point samples are suspect for reasons of size stratification within the duct.

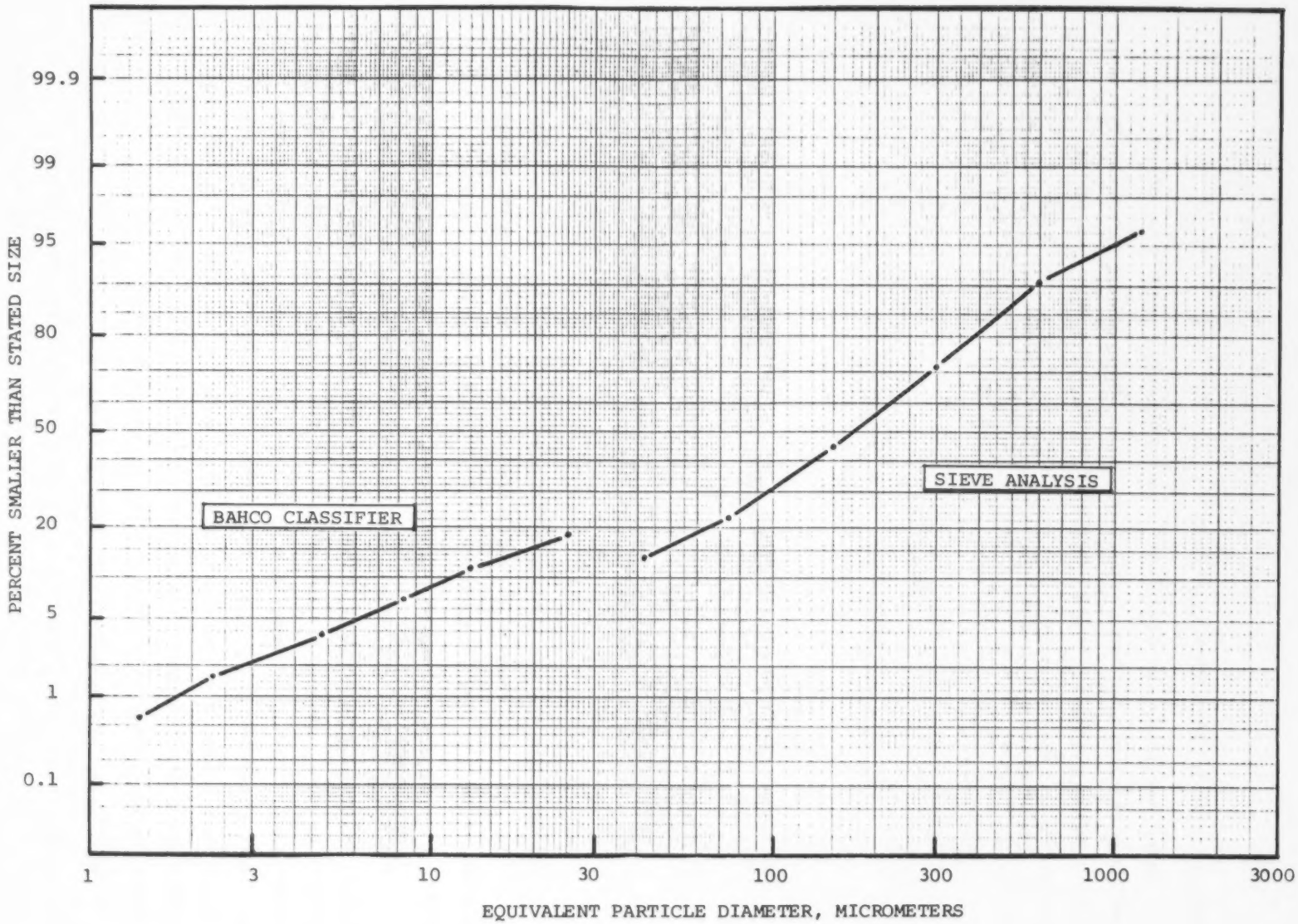

Figure 5-19. Uncontrolled Particle Size Distribution by Bahco Classifier and Sieve Analysis - Test Site H

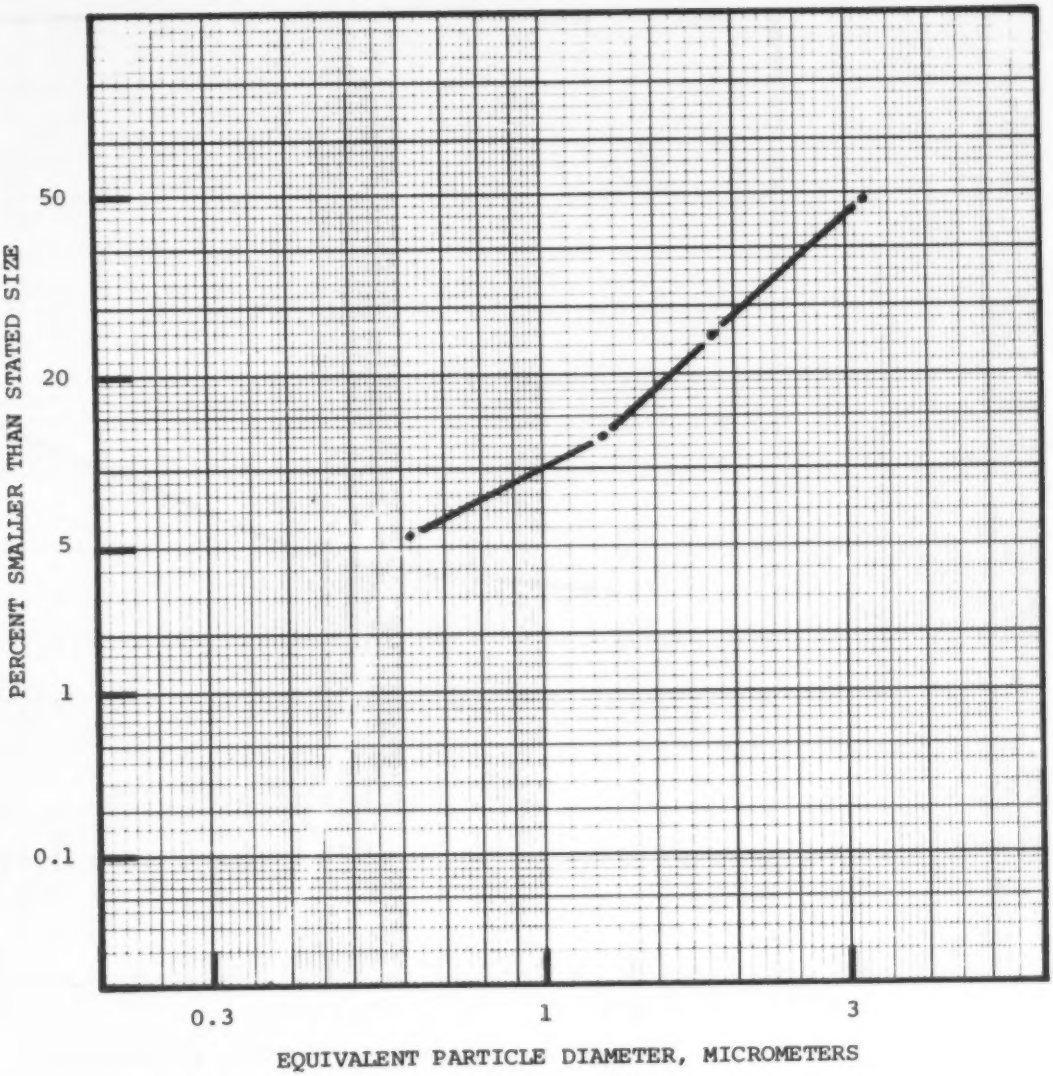

Figure 5-20. Uncontrolled Particle Size Distribution by Brink Cascade Impactor - Test Site H.

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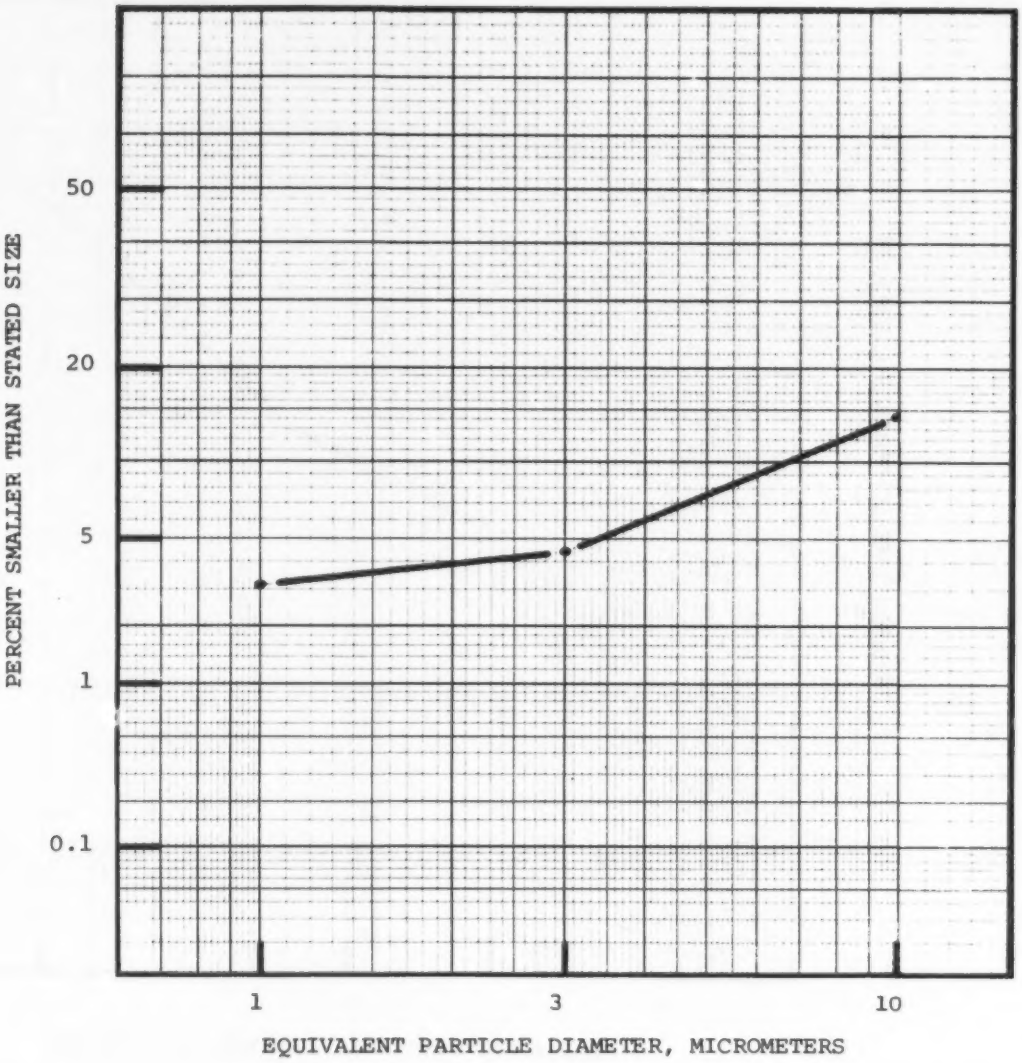

Figure 5-21. Uncontrolled Particle Size Distribution by SASS Cyclones - Test Site H.

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TABLE 5-16

RESULTS OF PARTICLE SIZE DISTRIBUTION TESTS
TEST SITE H

Test No.	Size Distribution % Below 3μm	% Below 10μm	Size Concentration lb/10^6Btu Below 3μm	10/10^6Btu Below 10μm	Sample Collection Efficiency %
3	2.2	8.7	0.048	0.191	87.8
5	45.0	--	0.509	--	100
11	4.42	14.21	0.097	0.312	100

5.5 SOURCE ASSESSMENT SAMPLING SYSTEM

One SASS test was run at Test Site H. All SASS test results will be reported under separate cover at the conclusion of this test program. The SASS sample catches will be analyzed by combined gas chromatography/mass spectroscopy for total polynuclear content. In addition, seven specific polynuclear aromatic hydrocarbons (PAH) will be sought. These are listed in Table 5-17.

TABLE 5-17

POLYNUCLEAR AROMATIC HYDROCARBONS
ANALYZED IN THE SITE H SASS SAMPLE

Element Name	Molecular Weight	Molecular Formula
7,12 Dimethylbenz (a) anthracene	256	$C_{20}H_{16}$
Dibenz (a,h) anthracene	278	$C_{22}H_{14}$
Benzo (c) phenanthrene	228	$C_{18}H_{12}$
3-methyl cholanthrene	268	$C_{21}H_{16}$
Benzo (a) pyrene	252	$C_{20}H_{12}$
Dibenzo (a,h) pyrene	302	$C_{24}H_{14}$
Dibenzo (a,i) pyrene	302	$C_{24}H_{14}$
Dibenzo (c,g) carbazole	267	$C_{20}H_{13}N$

5.6 DATA TABLES

Tables 5-18 through 5-21 summarize the test data obtained at Test Site H. These tables, in conjunction with Tables 2-1 and 2-2 in the Executive Summary, are included for reference purposes.

TABLE 5-18

UNCONTROLLED PARTICULATE EMISSIONS
TEST SITE H

Test No.	FIRING CONDITIONS Load %	O_2 %	OFA "H_2O	EMISSIONS lb/10^6Btu	gr/SCF	lb/hr	Velocity ft/sec
3	102	8.0	2.7	2.195	1.090	136	28.73
5	99	9.4	11.7	1.130	0.485	96	29.47
6	97	10.6	11.2	0.897	0.319	46	31.04
8	75	8.2	2.9	0.545	0.253	15	13.87
9	52	11.6	3.0	0.681	0.239	21	12.81

TABLE 5-19

HEAT LOSSES AND EFFICIENCIES
TEST SITE H

TEST NO.	DRY GAS LOSS	MOISTURE IN FUEL	H_2O FROM COMBUSTION OF H_2	COMBUSTIBLES IN FLYASH	COMBUSTIBLES IN BOTTOM ASH	TOTAL COMBUSTIBLES IN REFUSE	RADIATION FROM BOILER	UNMEASURED	TOTAL LOSSES	EFFICIENCY
03	12.77	1.14	4.17	0.87	1.54	2.41	0.64	1.50	22.63	77.37
05	13.93	1.43	4.31	0.37	2.52	2.89	0.65	1.50	24.71	75.29
06	13.85	1.45	4.40	0.32	2.67	2.99	0.67	1.50	24.86	75.14
08	10.23	1.20	4.22	0.24	2.60	2.84	0.86	1.50	20.85	79.15
09	12.13	1.12	4.04	0.32	2.14	2.46	1.23	1.50	22.48	77.52
11	17.54	1.20	4.39	0.60	0.38	0.98	0.65	1.50	26.26	73.74

TABLE 5-20

PERCENT COMBUSTIBLES IN REFUSE
TEST SITE H

Test No.	Boiler Outlet	Bottom Ash
3	--	19.57
5	23.0	20.72
6	25.2	14.56
8	30.5	18.18
9	33.4	18.10
11	--	7.10
AVG	28.0	16.37

TABLE 5-21

STEAM FLOWS AND HEAT RELEASE RATES
TEST SITE H

Test No.	Capacity %	Steam Flow* lb/hr	Heat Input** 10^6Btu/hr	Heat Output** 10^6Btu/hr	Front Foot Heat Release 10^6Btu/ft-hr	Grate Heat Release 10^3Btu/ft^2-hr	Furnace Heat Release 10^3Btu/ft^3-hr
1	87.8	39,500	52.3	39.8	4.03	373	28.3
2	96.0	43,200	57.2	43.5	4.40	408	30.9
3	101.6	45,700	60.5	46.0	4.66	432	32.7
4	49.9	22,433	29.7	22.6	2.29	212	16.1
5	99.0	44,533	59.0	44.8	4.54	421	31.9
6	97.3	43,800	58.0	44.1	4.46	413	31.3
7	75.5	33,975	45.0	34.2	3.46	321	24.3
8	74.8	33,666	44.6	33.9	3.43	318	24.1
9	51.9	23,333	30.9	23.5	2.38	221	16.7
10	50.8	22,875	30.3	23.0	2.33	216	16.4
11	100.0	45,000	59.6	45.3	4.58	425	32.2

* Steam Flow is based on panel board chart recordings because the steam flow integrator was out of calibration.

** Heat input is based on heat output divided by an average boiler efficiency of 76%. This was necessary because there was no accurate method of metering coal flow at Test Site H. Heat output is calculated from steam flow, steam pressure and feedwater temperature.

APPENDICES

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APPENDIX A

CONVERSION FACTORS

ENGLISH AND METRIC UNITS TO SI UNITS

To Convert From	To	Multiply By
in	cm	2.540
in^2	cm^2	6.452
ft	m	0.3048
ft^2	m^2	0.09290
ft^3	m^3	0.02832
lb	Kg	0.4536
lb/hr	Mg/s	0.1260
$lb/10^6$BTU	ng/J	430
g/Mcal	ng/J	239
BTU	J	1054
BTU/lb	J/kg	2324
BTU/hr	W	0.2929
J/sec	W	1.000
J/hr	W	3600
BTU/ft/hr	W/m	0.9609
BTU/ft/hr	J/hr/m	3459
$BTU/ft^2/hr$	W/m^2	3.152
$BTU/ft^2/hr$	$J/hr/m^2$	11349
$BTU/ft^3/hr$	W/m^3	10.34
$BTU/ft^3/hr$	$J/hr/m^3$	37234
psia	Pa	6895
$"H_2O$	Pa	249.1
Rankine	Celsius	C = 5/9R-273
Fahrenheit	Celsius	C = 5/9(F-32)
Celsius	Kelvin	K = C+273
Rankine	Kelvin	K = 5/9R

FOR TYPICAL COAL FUEL

ppm @ 3% O_2 (SO_2)	ng/J	($lb/10^6$Btu)	0.851 ($1.98x10^{-3}$)
ppm @ 3% O_2 (SO_3)	ng/J	($lb/10^6$Btu)	1.063 ($2.47x10^{-3}$)
ppm @ 3% O_2 (NO)*	ng/J	($lb/10^6$Btu)	0.399 ($9.28x10^{-4}$)
ppm @ 3% O_2 (NO_2)	ng/J	($lb/10^6$Btu)	0.611 ($1.42x10^{-3}$)
ppm @ 3% O_2 (CO)	ng/J	($lb/10^6$Btu)	0.372 ($8.65x10^{-4}$)
ppm @ 3% O_2 (CH_4)	ng/J	($lb/10^6$Btu)	0.213 ($4.95x10^{-4}$)
g/kg of fuel **			

*Federal environmental regulations express NOx in terms of NO_2; thus NO units should be converted using the NO_2 conversion factor.

** Based on higher heating value of 10,000 Btu/lb. For a heating value other than 10,000 Btu/lb, multiply the conversion factor by 10,000/(Btu/lb).

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APPENDIX B

CONVERSION FACTORS

SI UNITS TO ENGLISH AND METRIC UNITS

To Convert From	To	Multiply By
cm	in	0.3937
cm^2	in^2	0.1550
m	ft	3.281
m^2	ft^2	10.764
m^3	ft^3	35.315
Kg	lb	2.205
Mg/s	lb/hr	7.937
ng/J	$lb/10^6$BTU	0.00233
ng/J	g/Mcal	0.00418
J	BTU	0.000948
J/kg	BTU/lb	0.000430
J/hr/m	BTU/ft/hr	0.000289
$J/hr/m^2$	$BTU/ft^2/hr$	0.0000881
$J/hr/m^3$	$BTU/ft^3/hr$	0.0000269
W	BTU/hr	3.414
W	J/hr	0.000278
W/m	BTU/ft/hr	1.041
W/m^2	$BTU/ft^2/hr$	0.317
W/m^3	$BTU/ft^3/hr$	0.0967
Pa	psia	0.000145
Pa	$"H_2O$	0.004014
Kelvin	Fahrenheit	F = 1.8K-460
Celsius	Fahrenheit	F = 1.8C+32
Fahrenheit	Rankine	R = F+460
Kelvin	Rankine	R = 1.8K

FOR TYPICAL COAL FUEL

ng/J	ppm @ 3% O_2 (SO_2)	1.18
ng/J	ppm @ 3% O_2 (SO_3)	0.941
ng/J	ppm @ 3% O_2 (NO)	2.51
ng/J	ppm @ 3% O_2 (NO_2)	1.64
ng/J	ppm @ 3% O_2 (CO)	2.69
ng/J	ppm @ 3% O_2 (CH_4)	4.69
ng/J	g/kg of fuel	0.000233

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APPENDIX C

SI PREFIXES

Multiplication Factor	Prefix	SI Symbol
10^{18}	exa	E
10^{15}	peta	P
10^{12}	tera	T
10^{9}	giga	G
10^{6}	mega	M
10^{3}	kilo	k
10^{2}	hecto*	h
10^{1}	deka*	da
10^{-1}	deci*	d
10^{-2}	centi*	c
10^{-3}	milli	m
10^{-6}	micro	μ
10^{-9}	nano	n
10^{-12}	pico	p
10^{-15}	femto	f
10^{-18}	atto	a

*Not recommended but occasionally used

APPENDIX D

EMISSION UNITS CONVERSION FACTORS FOR TYPICAL COAL FUEL (HV = 13,320 BTU/LB)

To Obtain \ Multiply By	% Weight in Fuel		lbs/10^6Btu		grams/10^6Cal		PPM (Dry @ 3% O_2)		Grains/SCF. (Dry @ 12% CO_2)	
	S	N	SO_2	NO_2	SO_2	NO_2	SOx	NOx	SO_2	NO_2
% Weight In Fuel — S	1		0.666		0.370		13.2×10^{-4}		1.48	
% Weight In Fuel — N				0.405		0.225		5.76×10^{-4}		.903
lbs/10^6Btu — SO_2	1.50		1		(.556)		19.8×10^{-4}		(2.23)	
lbs/10^6Btu — NO_2		2.47				(.556)		14.2×10^{-4}		(2.23)
grams/10^6Cal — SO_2	2.70		(1.8)		1		35.6×10^{-4}		(4.01)	
grams/10^6Cal — NO_2		4.44		(1.8)				25.6×10^{-4}		(4.01)
PPM (Dry @ 3% O_2) — SOx	758		505		281		1		1127	
PPM (Dry @ 3% O_2) — NOx		1736		704		391				1566
Grains/SCF (Dry @ 12% CO_2) — SO_2	.676		(.448)		(.249)		8.87×10^{-4}		1	
Grains/SCF (Dry @ 12% CO_2) — NO_2		1.11		(.448)		(.249)		6.39×10^{-4}		

NOTE: 1. Values in parenthesis can be used for all flue gas constituents such as oxides of carbon, oxides of nitrogen, oxides of sulfur, hydrocarbons, particulates, etc.
2. Standard reference temperature of 530°R was used.

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APPENDIX E

UNITS CONVERSION FROM PARTS PER MILLION (PPM) TO POUNDS PER MILLION BTU INPUT ($LB/10^6BTU$)

$$lb/10^6Btu = (ppm)\left(\text{fuel factor}, \frac{SCF}{10^6Btu}\right)(O_2 \text{ correction, n.d.})\left(\text{density of emission}, \frac{lb}{SCF}\right)(10^{-6})$$

$$\text{Fuel factor}, \frac{SCF^*}{10^6Btu} = 10^6[1.53C + 3.61H_2 + .14N_2 + .57S - .46O_2] \div (Btu/lb)$$

where C, H_2, N_2, S, O_2 & Btu/lb are from ultimate fuel analysis;

(a typical fuel factor for coal is 9820 $SCF/10^6Btu \pm 1000$)

O_2 correction, n.d. = $20.9 \div (20.9 - \%O_2)$

where $\%O_2$ is oxygen level on which ppm value is based;

for ppm @ 3% O_2, O_2 correction = $20.9 \div 17.9 = 1.168$

Density of emission = SO_2 - 0.1696 lb/SCF*

NO - 0.0778 lb/SCF

CO - 0.0724 lb/SCF

CH_4 - 0.0415 lb/SCF

to convert $lbs/10^6Btu$ to ng/J multiply by 430

* Standard conditions are 70°F, 29.92 "Hg barometric pressure

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